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Policy options to enhance technology diffusion: modeling the greenhouse gas reduction potential of solid-state lighting

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Policy Options to Enhance Technology Diffusion:
Modeling the Greenhouse Gas Reduction Potential of Solid-State Lighting

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ABSTRACT

Solid-state lighting (SSL) is an emerging technology that is projected to provide substantial energy savings over conventional lighting sources by 2025. There is a growing concern over the consequences of climate change, largely attributed to anthropogenic emissions of carbon dioxide (CO_2; a greenhouse gas) from fossil fuel combustion. Currently fossil-fuel combustion accounts for 70% of electricity produced in the U.S., and end-use lighting applications alone consume approximately one-fifth of this electricity. Therefore, replacing conventional lighting sources with energy-efficient SSL has the potential to significantly reduce electricity consumption which can in turn reduce CO_2 emissions.

However, previous research has shown there is a so-called “energy-efficiency gap” between the energy-efficient technologies that are available at a point in time, and those that are actually used. Thus, while the innovation of new energy-efficient lighting holds the potential to reduce the intensity of energy use in buildings, this savings will not be realized unless these energy-efficient technologies are adopted by consumers. This research has two primary objectives: (1) to quantify the reductions in carbon dioxide emissions which can be achieved through the diffusion of SSL through the commercial building sector, and (2) to explore how policies might be used to accelerate the diffusion of SSL technology into the commercial building sector.

This thesis uses simulation modeling to explore SSL technology diffusion in the commercial building sector. A solid-state lighting commercial market penetration (SSL CMP) model is constructed in STELLA, a graphical dynamic simulation software tool. The SSL CMP model simulates the process of SSL technology diffusion between 2005 and 2025, and calculates the CO_2 emission reductions which will accompany the adoption of this new technology. The model is based on a probit model of technology diffusion, but will also incorporate the epidemic theory of diffusion.

Policy instruments are tested using the SSL CMP model to demonstrate how they can affect the diffusion of SSL and the CO_2 reductions which can be gained through such efforts. The policy instruments used in this analysis include: research and development (R&D); an electricity tax; a rebate; and an information program. Combinations of these policy instruments are used in six different scenarios. These scenarios are simulated by incorporating these policies into the SSL CMP model and simulating technology diffusion through 2025. In this analysis, Scenario 3 (Accelerated R&D) generates the most significant environmental benefit – a 45% reduction from projected CO_2 annual emissions due to commercial lighting in 2025. Scenario 2 (Medium R&D) is able to achieve a 23% reduction of emissions by this year. The rebate policy is found to generate earlier SSL market adoption and emission reductions, by approximately two years. The information program is able to accelerate the rate of market adoption. Finally, the vast majority of energy savings are found to be from one sector of the commercial building lighting market: the very high color rendering index (VH CRI) bin, indicating that incandescent lighting should be the focus of policy efforts to replace conventional lighting with SSL.

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ACRONYMS & ABBREVIATIONS

AEO	Annual Energy Outlook
CFL	Compact fluorescent lamp
CL	Conventional lighting
CO_2	Carbon dioxide
DOE	Department of Energy
DSM	Demand-side management
EIA	Energy Information Administration
EPA	Environmental Protection Agency
GHG	Greenhouse gases
HID	High intensity discharge
HB LED	High brightness light-emitting diode
IPCC	Intergovernmental Panel on Climate Change
IRP	Integrated resource planning
LED	Lighting-emitting diode
NEMS	National Energy Modeling System
NGLI	Next Generation Lighting Initiative
OIDA	Optoelectronics Industry Development Association
OLED	Organic light-emitting diode
OTA	Office of Technology Assessment
R&D	Research and development
SSL	Solid-state lighting
SSL CMP	Solid-state lighting commercial market penetration (model)
UNFCCC	United Nations Framework Convention on Climate Change
UV	Ultra-violet

CHAPTER I. INTRODUCTION

Solid-state lighting (SSL) is an emerging energy-efficient lighting technology that has the potential to revolutionize lighting markets. The energy-efficiency potential of SSL has been a major driving force to develop this innovative technology. Today, scientific consensus is growing over the threat posed by global climate change. Anthropogenic activities are increasing the atmospheric concentration of greenhouse gases (GHGs). The heat-trapping property of these GHGs – primarily carbon dioxide (CO_2), methane, nitrous oxide and chloroflorocarbons – are undisputed. As these GHGs accumulate in the atmosphere, they are causing surface air temperatures and subsurface water temperatures to rise (NRC, 2001). According to the Intergovernmental Panel on Climate Change (IPCC), the increase in the surface temperature in the Northern Hemisphere during the 20th Century is likely greater than any increase over any century in the last one thousand years (IPCC, 2001).

Currently, energy-related activities account for an overwhelming 82% of U.S. anthropogenic GHG emissions, and lighting as an end-use is a significant consumer of energy (EIA, 2003a). Developing cleaner energy technologies and diffusing them through the market is vital for lowering emissions of CO_2, the primary GHG. Yet, an abundance of research conducted over the last two decades has consistently shown that cost-effective energy-efficient technologies experience very slow rates of adoption (Brown, 2001; Jaffe & Stavins, 1994b). Therefore, while SSL holds significant energy-efficiency potential, simply developing this technology will not be sufficient. The environmental benefits of greater energy-efficiency will only be realized if SSL is widely diffused through lighting markets.

The purpose of this research is to explore the following questions:

(1) What reductions of CO_2 emissions can be achieved through the diffusion of SSL into the commercial building sector? and;

(2) What policies might be used to accelerate the diffusion of SSL technology into the commercial building sector?

Global climate change is one of the most serious environmental problems facing this and future generations. Average global temperatures have risen by approximately 0.6 °C (1.1 °F) in the last century, and this trend is expected to continue and even accelerate over the 21st century (IPCC, 2001). As the warming continues, the effects of climate change are likely to have adverse impacts on environmental and socio-economic systems throughout the world, although the extent of these impacts is highly sensitive upon the rate and the magnitude of the climate change over the next century (IPCC, 2001). According to the U.S. Environmental Protection Agency (EPA), the U.S. will likely experience greater and more intense precipitation, and changes in local climates as a result of a rising global temperature (EPA, 2000). These changes could have wide-reaching impacts on natural systems such as coastal zones, water resources, mountains and forests, and deserts, as well as on human health and the economy. For example, New York State could be 4.0 ˚F higher in the winter and spring, and slightly more in the fall and summer by 2100 (EPA, 1997). The frequency of extremely hot days in the summer could increase, which in turn would lead to a higher number of heat-related deaths and incidents; for example the EPA estimates that a 1.0 ˚F change in temperature could increase the number of heat-related deaths in New York City over a typical summer from 300 today, to over 700 (EPA, 1997).

There is growing consensus in the scientific community that this warming trend is a result of rising atmospheric concentrations of GHG (NRC, 2001). The U.S. currently emits more GHGs per person than any other country, and in 1998 was responsible for 25% of the worldwide GHG emissions (EPA, 2004). In the U.S., fossil fuel energy sources (including coal, natural gas, and oil) are used to generate approximately 70% of U.S. electricity (EIA, 2004a). When fossil fuels are burned to extract energy, CO_2, one of the primary GHGs is released into the atmosphere. According to the U.S. Energy Information Administration (EIA), 39% of total U.S. CO_2 emissions were attributed to electricity generation from fossil fuels in 2002 (EIA, 2003a).

Innovative energy technologies can play an important role in curbing emissions of CO_2. Solid-state lighting is one example, which has received considerable attention in recent years. This lighting technology has the potential to become significantly more energy-efficient than lighting technologies currently used (*e.g.*, incandescent and fluorescent). Presently in the U.S., approximately 22% of the electricity generated is used for lighting. Put into a broader context, the Department of Energy (DOE) estimates that 8.3% of U.S. primary energy consumption goes to lighting (DOE, 2002). Solid-state lighting has the potential to significantly reduce the electricity needed for lighting. Estimates for lighting energy savings potential have been as optimistic as a 50% reduction by 2025, which would decrease total U.S. electricity consumption by about 10% (Tsao, 2004). Recent analysis conducted by the DOE using a SSL market penetration model found that by 2025, SSL use for general illumination in the U.S. could reduce the amount of electricity used for lighting by 33% (DOE, 2003b).

Policies that promote technological innovation are an important strategy for reducing GHG emissions. Well-designed policies to develop and diffuse new environmentally-benign technologies have the potential to play an important role in reducing the emission of GHGs and mitigating the impacts of climate change. These technological advancements can be realized by (1) increasing the efficiency of energy using technologies in order to reduce energy demand; (2) substituting high-carbon energy technologies with low- or zero-carbon technologies; (3) sequestering the carbon either before or after it enters the atmosphere; and (4) developing technology which reduces the emissions of GHGs other than CO_2 (Alic, Mowery, & Rubin, 2003).

Solid-state lighting is an emerging energy-efficient technology with the potential to fulfill the first of the four technology pathways identified above. Research and development (R&D) is currently ongoing throughout the world to develop white SSL suitable for general illumination.[1] The DOE and SSL industry have recognized this opportunity and are pushing for a national initiative to accelerate the development of this promising technology (Haitz, Kish, Tsao, & Nelson, 2000). Solid-state lighting is eventually expected to become approximately twice as efficient as fluorescent lighting, and up to ten times as efficient at incandescent lighting.

[1] General illumination is the lighting required to perform tasks, and is commonly divided into three types: ambient, task, and accent lighting. See Appendix A for further information.

Despite the promising potential of SSL, the benefits of this technology will only be realized when this technology is widely adopted through the market, replacing less efficient incumbent lighting technologies. Realizing these widespread benefits will require three steps:

- *invention* – the development of a new technological idea;
- *innovation* – the transformation of that new technological idea into a commercial product or product; and
- *diffusion* – the gradual adoption of this new commercial product or process by potential users (Jaffe & Stavins, 1991).

This research focuses on the diffusion process of SSL to better understand how alternative policy scenarios can affect the diffusion trajectory, and thus ultimately impact U.S. CO_2 emissions. A solid-state lighting commercial market penetration (SSL CMP) model is built using STELLA,[2] a systems modeling software tool. The SSL CMP model simulates the market penetration of SSL into the general lighting market in the U.S. commercial building sector. This model is used to test the effect that alterative policies have on the diffusion of SSL and consequentially, CO_2 emissions. These policies are incorporated into six scenarios and these scenarios are then simulated over a 20 year time period from 2005 until 2025.

[2] STELLA® software version 8 is used in this analysis and is produced by isee systems, inc. found online at http://www.iseesystems.com/

The rest of this thesis is structured as follows:

Chapter II provides a comprehensive literature review on incumbent lighting technologies and the energy they consume in the U.S. This literature review includes a high-level technology assessment of the technical, economic and market potential of SSL. An overview is given on the widely debated “energy-efficiency gap,” and the barriers to realizing a higher level of energy-efficiency. An overview of the gradual process of technology diffusion as it relates to all new technologies is provided. The government’s role in promoting energy-efficient technologies is discussed.

Chapter III explains the methodological approach of systems modeling chosen for this study. A brief overview of energy-economic modeling is provided in the first section of the chapter. The rest of the chapter provides a detailed explanation on the structure of the solid-state lighting commercial market penetration (SSL CMP) model, including data sources and the relationships between elements of the model. Finally, the chapter concludes with an overview of the six policy scenarios created and tested using this model.

Chapter IV presents the results from simulating the six policy scenarios described in Chapter III, using the SSL CMP model. The energy and CO_2 impacts under each scenario are analyzed. The epidemic dynamic and its role in diffusion SSL are also discussed. Finally, the results from a sensitivity analysis are explained in order to better understand how sensitive the outcomes are to particular inputs and assumptions used in the model.

Chapter V summarizes the findings of the six scenarios tested using this model. Conclusions are drawn as to impact different policies will have on the rate of SSL diffusion into the general illumination market for the U.S. commercial building sector, and several policy recommendations are made. Limitations of this analysis are discussed and based on the research conducted in this study, future research directions are suggested.

CHAPTER II. LITERATURE REVIEW

1. Chapter Overview

This chapter reviews the background literature necessary for modeling how solid-state lighting (SSL) will penetrate the market and what policy mechanisms might be used to accelerate market diffusion. First, to estimate future SSL market adoption, it is necessary to gain a sense of the current lighting market for general illumination. The next section provides a brief description of each main type of lighting technology – in particular, how they are used in the U.S. commercial building sector. The annual energy consumption of lighting is then discussed, followed by an overview of the carbon dioxide (CO_2) emissions that are released to generate this energy. Section three provides an overview of SSL technology and the drivers for, and barriers to, its widespread use in general illumination. The fourth section discusses several conceptual models used to describe how new technologies are diffused through the market. Finally, the fifth section discusses the well documented "energy-efficiency gap," and potential for policy interventions to close this gap and accelerate the diffusion of new energy-efficient technologies.

2. The U.S. General Illumination Market

Artificial lighting is an essential service in the modern world, and provides people with the light necessary to perform a wide variety of visual tasks. Solid-state lighting has the potential to become a revolutionary lighting technology by ushering in an entirely new lighting paradigm. One major benefit that is propelling this transition forward is the potential for energy savings from the development and adoption of highly efficient SSL. Lighting can be thought of as serving two distinct purposes: indication and illumination. The former is viewed directly by people, for example a traffic light, or the indicator light on a computer. The latter is instead used to illuminate objects, which are then viewed. It is the latter of these – illumination – on which this thesis is specifically directed.

2.1 Overview of Lighting Technologies

Today, there exists a large and diverse portfolio of technologies which provide illumination service. These lighting technologies can be broadly classified into four main groups: incandescent, fluorescent, high-intensity discharge (HID), and most recently, SSL. The first three of these lighting technology groups are currently used in the commercial building sector, which is the focus in this study.

Below are brief overviews of these four groups of lighting technologies.[3] Solid-state lighting is discussed in much greater detail in the following section of Chapter II. Definitions of lighting terminology used throughout this thesis can be found in Appendix A.

Incandescent

The incandescent lamp was invented in the late 1800s by Thomas Edison in America and simultaneously by Joseph Swan in England, and today these lamps provide most of the light used by households. They are also widely throughout commercial buildings (Vorsatz, Shown, Koomey, Moezzi, Denver, & Atkinson, 1997). Incandescent lamps are very inefficient because 90-95% of the emissions are in the infrared (thermal) rather than the

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[3] These four classifications of lighting technologies all include a number of different sub-classifications of lamp types. These sub-classifications are found in Appendix B.

visible range of the electromagnetic spectrum. Incandescent lamps today have efficiencies or "efficacies," ranging from 13-25 lumens per watt[4] (DOE, 2003b).

Incandescent lamps operate by passing electrical current through a metal filament that is heated to the point of incandescence. Today, these metal filaments are most commonly made of tungsten. Very recent technological advances have shown that with further research, a nanotube filament composed of carbon nanotubes might one day be used as more energy-efficient filament for incandescent lamps (Wei, Zhu, & Wu, 2004).

Despite the inefficiency of incandescent lamps, they provide several important advantages over other light sources. These advantages include: an excellent color rendering index (CRI)[5] and a warm color, the ability to be easily dimmed, inexpensive, small and lightweight, compatibility with inexpensive fixtures, and the simplicity of purchasing, installation, maintenance, and disposal (Atkinson, Denver, McMahon, Shown, & Clear, 1995). These lamps are the most prevalent in the residential sector, accounting for an estimated 86% of the lamps used by households and consuming 90% of the electricity used for household lighting (DOE, 2002). Incandescent lamps are also widely used in the commercial sector, representing approximately 22% of the installed lamps and consuming 32% of the electricity used for lighting in the commercial sector (DOE, 2002).

[4]Lumens are a basic unit measurement of light. A lumen is defined as the amount of light given out through a solid angle by a source of one candela [unit of luminous intensity] radiating out equally in all directions. "Efficacy" is the terminology used to express the energy-efficiency of lighting, and is calculated by dividing the quantity of light emitted from the lamp (in lumens) by the power input to the lamp (in watts).

[5] The color rendering index (CRI) of a lamp is a measure of how surface colors appear when illuminated by the lamp, compared to how they appear when illuminated by a reference source of the same temperature. The CRI scale extends from 0 up to 100, with 100 representing the "best," indicating that the light in question is able to render the color of the object very well.

Fluorescent

Fluorescent lamps were first produced in the U.S. in the late 1930s, and came into general use by the 1950s (Atkinson et al., 1995). Fluorescent lamps produce light by applying a high voltage across two electrodes, initiating an electric arc discharge that ionizes the evaporated mercury in the lamp. The ionized mercury emits mostly ultra-violet (UV) radiation, which strikes and excites the phosphorus coating on the tube causing fluorescence and producing visible light. These lamps must operate in conjunction with a ballast. The purpose of the ballast is to limit the incoming current to a certain value and to provide the needed start-up and operating lamp voltages. The most common fluorescent lamps are tubular and four-feet long. The efficacies of fluorescent lamp (including ballast losses) range between 60-90 lm/W. The efficacies of fluorescent lighting also depend on the type of ballast used: efficiencies are higher with electronic ballasts than with magnetic ballasts. A significantly smaller version of the fluorescent lamp – the compact fluorescent lamp (CFL) – was introduced in the early 1980s as a more energy-efficient and longer lasting alternative to incandescent lamps. Compact fluorescent lamps have efficacies of approximately 55 lm/W.

Fluorescent lamps are most commonly used in the commercial and industrial sectors. In the commercial sector they account for 77% of the installed lamps and consume 56% of the total electricity for lighting used in the commercial sector. In the industrial sector they account for 93% of the installed lamps and consume 67% of the electricity that goes to lighting (DOE, 2002). On the other hand, fluorescent lighting is limited in the residential sector and when used, it is generally restricted to kitchens, bathrooms and utility areas

(Vorsatz et al., 1997). Compact fluorescent lamps have been on the market since the 1980s but initially experienced very slow adoption rates. In recent years CFLs have begun to gain greater market share within market of retail screw-based lamps, with national sales reaching 2.1% of this market by the end of 2001 (Calwell & Zugel, 2003).

High-Intensity Discharge

High-intensity discharge (HID) lamps operate similarly to fluorescent lamps in that they initiate an arc discharge though a mixture of gases, and they require a ballast to regulate their voltage and current. However, HID lamps differ from fluorescent light sources in that they operate at very high temperatures and pressures. The three primary types of HID lamps are mercury vapor (MV), metal halide (MH), and high-pressure sodium (HPS). These lamps are the most effective when used in applications with limited start-ups and shut-downs because of the time they require for starting, which can vary from 2-15 minutes depending on the lamp type and whether it is starting (cold start) or restriking (hot start). Including ballast losses, the efficacies of these three HID technologies are: mercury vapor lamps (25-50 lm/W), metal halide lamps (46-100 lm/W), and high-pressure sodium (50-124 lm/W) (Atkinson et al., 1995). Generally HID lamps are used where the color of the light is not a high priority.

HID lamps are most widely used in the outdoor stationary sector, as well as in commercial and industrial sectors.[6] In the outdoor stationary sector, they account for 75% of lamp installations, and consume 87% of the electricity used for lighting in this sector (DOE,

[6] This "stationary outdoor" sector was used in the 2002 report *US Lighting Market Characterization* commissioned by the Department of Energy. This sector includes lighting installations such as street lighting, airport runway systems, traffic signals and billboard lighting. Outdoor lighting from mobile sources such as automobiles is not included.

2002). In the commercial and industrial sectors, HID lamps account for 2% and 5% of lamp installations. They consume 11% and 30%, respectively, of the electricity used for lighting in the commercial and industrial sectors (DOE, 2002).

Solid-State

Solid-state lighting is an emerging and promising lighting technology, which uses either light-emitting diodes (LEDs) or organic light emitting diodes (OLEDs) as a light source. To date, LED technology is further advanced than OLED technology, and thus is expected to be the first to enter into the market for general illumination (Tsao, 2004). However both are expected to eventually play a role in the lighting market. The advantages of light-emitting diode solid-state lighting (LED-SSL) over more conventional lighting technologies include their low energy consumption, longer lifetime, ruggedness and durability, compactness, safety from a low operating current, fast "on" time, operability in low temperature applications, dimmability, easy installation, and directionality.

Many of these inherent advantages of LEDs over conventional lighting sources have already allowed them to penetrate into the market for niche application lighting. For instance, LEDs inherently produce monochromatic light and hence are a natural choice for indication applications such as traffic lights and exit signs, which require colored light. In these cases, the need to use an incandescent light coupled with a filter to convert white light to colored light (an inefficient process), is eliminated. Niche lighting applications in which the compactness, ruggedness, and longevity of LEDs provide a comparative advantage have also been penetrated by LEDs. Creating truly white energy-efficient SSL to be used as general illumination is the greatest challenge of all, but experts are optimistic that in time it will be accomplished. The challenges facing SSL in the general illumination market are discussed in the next chapter.

In this study, incandescent, fluorescent, and HID technologies are the incumbent lighting technologies that SSL unseats to gain market share. Within the model that has been built for this study, the lighting market is broken down into four CRI bins: very high CRI (91-100); high CRI (76-90); medium CRI (41-75); and low CRI (0-40). Each individual lighting technology has been placed in one of these four bins, depending on its CRI value. The very high CRI (VH CRI) bin encompasses all incandescent lighting technologies, while fluorescent technologies either fall into the high CRI (H CRI) or medium CRI (M CRI) bin. HID technologies tend to have low CRI (L CRI) values and thus are predominately found in the L CRI bin. The breakdown into CRI bins is consistent with the method used in the DOE SSL market penetration model (DOE, 2003b). Further detail on the data and the methodology used to develop the model for this study has been included in Chapter III.

2.2 Energy Consumption

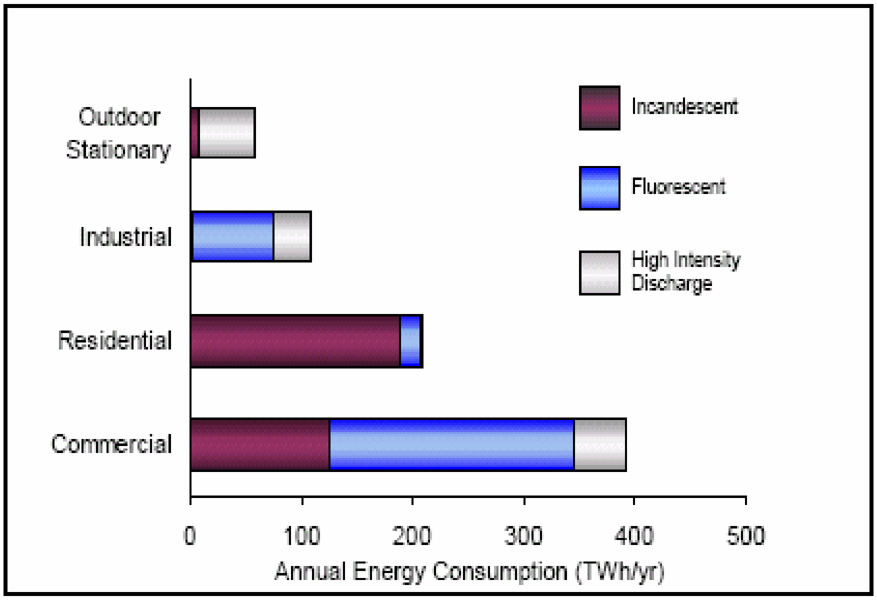
The Department of Energy (DOE) recently commissioned a multiyear study to evaluate lighting in the U.S. and identify opportunities for energy savings (DOE, 2002). The report from this study contains the most up-to-date data on U.S. lighting patterns and consumption. The first phase of the study, *U.S. Lighting Market Characterization: Volume I - National Lighting Inventory and Consumption Estimate* found that lighting for general illumination in the U.S. (taking into account generation and transmission losses) consumed a total of 8.2 quads of primary energy in 2001, which is equivalent to 765 Terawatt-hours (TWhr) at the building site (DOE, 2002).[7]

To understand the significance of lighting as an end-use consumer of electricity and identify energy-efficiency opportunities, it is helpful to put this figure into a broader context. In 2001, the total amount of energy consumed by the U.S. was approximately 98.3 quads of energy, more than a third of which – 37 quads, was used to generate electricity. Of this electricity generated, lighting as an end-use accounted for approximately 22% of electricity consumption.[8] This translates into lighting consuming approximately 8.3% of the national primary energy consumption in 2001.

In Figure II-1 the commercial sector is seen to be by far the largest consumer of electricity for lighting, with substantial energy consumption by incandescent, fluorescent and HID technologies. The commercial sector's energy demand in 2001 was 391TWhr and accounts for just over 50% of the total electricity consumed for lighting in the U.S. in that year.[9] The residential sector is the second largest lighting energy consumer, consuming 27% or 208 TWhr/yr. The industrial and outdoor stationary sectors consume 14% and 8% respectively, of the electricity used for lighting. The commercial sector was chosen to be the focus of this study because of its significance as an end-consuming sector of energy for lighting.

[7] The conversion factor (incorporating generation, transmission and conversion losses) used for site-use energy to primary energy consumed at the generating power plant was 10,768 BTU/kWh for the year 2000. See Appendix C for a complete list of conversion factors and units used in this thesis.
[8] In addition, the excess heat given of by lighting systems leads to additional electricity consumption. Researchers have estimated that 3-4% of national electricity can be indirectly attributed to lighting systems, due to the air conditioning electricity consumption that is needed to cool off the buildings from the heat generated from lighting. (Atkinson et al., 1995)
[9] The prefix "tera" denotes 10^12, and hence 1 TWhr = 1,000,000,000,000 Whr.

Figure II-1. U.S. Energy Consumption for Lighting in 2001
(Per Sector by Lamp Type)



Source: (DOE, 2002) Figure ES-1

Energy consumption data for lighting is an essential component to planning effective lighting research and development activities. Due to current lighting inefficiencies there is a high potential for electricity savings through the use of more energy-efficient lighting technologies, as well as more advanced lighting designs and control strategies (Atkinson et al., 1995). Of the total primary energy consumed by the commercial sector, lighting as an end-use accounts for approximately 25%. Lighting is by far and away the largest end-user of electricity in this sector (Interlaboratory Working Group, 2000). The commercial building sector lighting data used for this study will be discussed in further detail in the following chapter.

2.3 Environmental Impact

The adoption of energy-efficient technologies allows for the same level of energy service to be carried out, with less energy input. Environmentally, this has important benefits because of the environmental externalities which are associated with producing energy. This thesis focuses on

CO_2 emissions from electricity generation. While there are additional environmental and social impacts that accompany energy use, an analysis of these impacts falls outside the scope of this study.

Currently in the U.S., approximately 70% of electricity is generated from fossil fuel sources (EIA, 2004c). The production of energy from fossil fuel sources releases a significant quantity of airborne pollutants, including CO_2, nitrous oxides, sulfur dioxides, and mercury. In particular the emissions of CO_2 have drawn significant attention because growing concerns over global climate change.   There remain scientific uncertainties over climate change – for instance – exactly how much of the warming in the last century can be attributed to anthropogenic activities and how much is a result of natural fluctuations in temperature.   But despite uncertainties, the Intergovernmental Panel on Climate Change (IPCC) wrote in 1996 that “the balance of evidence suggests there is a discernable human influence on climate change” (IPCC, 1996).

Although many greenhouse gases (GHG) occur naturally in the atmosphere, anthropogenic activities add to the concentrations of some of these gases in the atmosphere, including CO_2, methane, nitrous oxide, and ozone.   Human activities alone have also added additional GHG to the atmosphere, including hydrofluorocarbons, perfluorocarbons and sulfur hexafluoride. When GHG accumulate in the atmosphere, they trap outgoing radiation and warm the earth’s atmosphere.

By convention, each GHG is converted via its global warming potential (GWP), so that the potency of each gas’s contribution to global warming can be comparatively assessed. The GWP is a ratio of the warming from one mass unit of a GHG, to that of one mass unit of CO_2 over a specific time period. Since 1992 the U.S. Environmental Protection Agency has prepared an annual report, *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, in accordance with the United Nations Framework Convention on Climate Change (UNFCCC). This emissions inventory details the characteristic and physical identity of pollutants, types of activities which release emissions, and the time period over which emissions occur for all human-generated GHG emissions in the U.S. (EPA, 2002). In the U.S., when all GHG are converted to metric tons of carbon dioxide equivalent, energy-related CO_2 emissions in 2002 comprised 82.8% of total GHG emissions (EIA, 2003a). Of the 5,786 million metrics tons (MMT) of CO_2 emissions in 2002, approximately 38% was from the U.S. electric power sector (EIA, 2003a).[10] Lighting consumes 22% of all electricity generated in the U.S. (DOE, 2002), and therefore accounted for roughly 420 MMT of CO_2 2002. Hence, commercial lighting which accounts for just over 50% of total lighting energy consumption was responsible for approximately 215 MMT CO_2 in 2002.

Policies that promote technological innovation are an important strategy for reducing CO_2 emissions. Well-designed policies to encourage the development and diffusion of new environmentally benign technologies will be an important contributor to reducing the emissions of CO_2 and mitigating climate change.   SSL is one example of an emerging technology, which promises to consume considerably less energy than other lighting technologies while delivering the same, or even improved, lighting service. However, while SSL could reduce energy consumption, the actual carbon emissions reductions realized from higher energy-efficiency will depend on additional factors. These factors include the thermal efficiency of power plants as well

[10] The electric power sector as defined by the EIA includes utilities, independent power producers, and combined heat and power facilities whose primary business is the production and sale of electricity. (EIA, 2003a)

as distribution losses as electricity is transported over the grid, and the mix of energy sources used to generate the electricity. In this study, the thermal efficiency and distribution losses will be held constant. However the mix of energy sources (oil, natural gas, coal, nuclear, and other) used to create electricity will be incorporated into the model as a variable.

Fossil fuels, including natural gas, coal, and oil, have different carbon intensities. Therefore, each fuel produces a different amount of carbon per unit of energy content. Coal for instance is the most carbon-intensive, while oil produces about 25% less carbon per unit of energy content, and natural gas about 45% less. In this study, the carbon emissions factors of energy sources are built into the model, to link the adoption of SSL to specific reductions in CO_2. The model has been built so that a user can change the particular mix of energy sources used to generate electricity, or can even vary this fuel mix over time. Additional air pollutants released from electric power plants include nitrous oxides, sulfur dioxides, and mercury – however these pollutants and their emissions factors will not be incorporated into the model at this time.

3. Technology Assessment of Solid-State Lighting

Scientists and industry experts are predicting that SSL will likely become a revolutionary force in the lighting industry (DOE, 2003b; Johnson, 2000; NRC, 2002). This emerging lighting technology has potential to become significantly more energy-efficient than lighting technologies that are currently used (*e.g.,* incandescent and fluorescent lighting).

The term “solid-state lighting” is used to encompass both organic light-emitting diodes (OLEDs) and inorganic light-emitting diodes (LEDs).[11] Currently, LED technology is more advanced and projected to enter into the market first (Tsao, 2004). However it is expected that both technologies will eventually play a role in SSL applications. It is important to note that a market penetration model used by DOE (2003a) takes into account both LEDs and OLEDs under a combined general set of future cost and performance characteristics. Two sets of future cost and performance trends (one under an accelerated investment scenario and one assuming a moderate investment scenario) were developed in consultation with SSL industry experts. These cost and performance trends have been incorporated into the model used in this thesis.

Below is a description of LED technology, including the underlying science and a brief historical timeline of the development of LEDs. The focus has been placed on LED technology rather than OLED technology, because the former is currently further advanced and is projected to enter the market for general illumination first (Tsao, 2004).

3.1 Overview of Light-Emitting Diodes

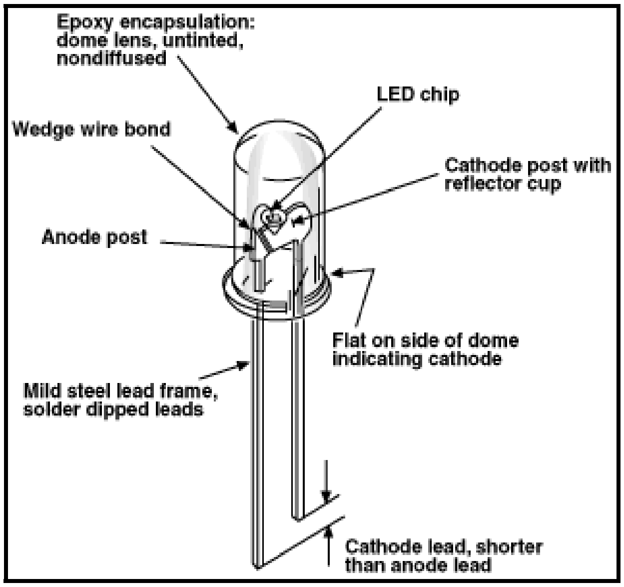
Light-emitting diodes are based upon the scientific principles of injection luminescence, in which electrons and holes combine (also known as radiative recombination) within the active region of semiconductor materials, and emit photons (*e.g.*, light). The most basic structure of an LED is that of a semiconductor diode, in which the active region where the electrons and holes recombine is the junction between the n-type and the p-type semiconductor materials. Most LEDs use compound semiconductors and varying the particular semiconductor materials used

[11] Organic lighting emitting diodes (OLEDs), which are based upon flexible plastic materials (polymers) have their own set of technical challenges. However OLEDs also expected to be a player in the general illumination market particularly because they don’t need to be manufactured in (costly) semiconductor fabrication facilities.

changes the wavelength (color) of the emitted light. In the basic LED structure, electrodes are fixed to the LED chip, and the chip is encapsulated within a dome shaped lens.

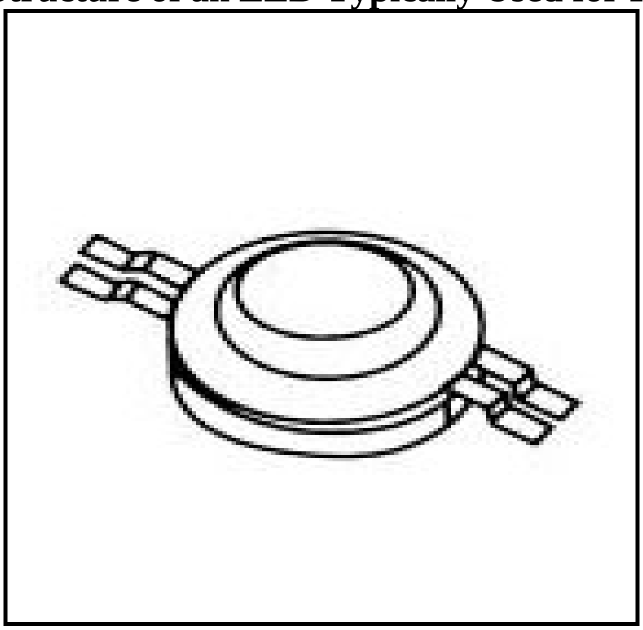
Semiconductor materials have been used to generate light for over forty years. In 1962 the first LED was invented by Nick Holonyak Jr. at General Electric (NRC, 2002). Six years later LEDs were commercially introduced by Monsanto and Hewlett-Packard (Haitz et al., 2000). The first application of LEDs was as indicator lights on electronic devices, with later applications expanding to the dots and bars seen on alphanumeric displays in the first electronic watches and calculators (Zukauskas, Shur, & Gaska, 2002). Subsequent gradual improvements in efficiency and longevity, as well as the technological breakthrough creating a blue LED in the mid-1990s, have enabled the development of "white" solid-state lighting to become a reality. Today, high-brightness LEDs (HB LEDs) operate on higher currents than older generation LEDs which remain prevalent – for example, as small indicator lights on consumer electronic devices. These HB LEDs are able to generate greater light (or lumens) output, which has allowed LED technology to be extended to lighting applications that require greater luminous output. Because of their inherent monochromatic nature, LEDs have been tremendously successful in a number of niche applications that require colored light such as traffic signals and exit signs. In these markets, it is estimated that by 2002 LEDs had captured 30 and 70% respectively, of these two niche markets (DOE, 2003a). The basic structure of the tradition LED and the structure of a LED which is commonly used for illumination purposes are depicted below in Figures II-2 and II-3, respectively.

Figure II-2. Basic Structure of an Indication LED



Source:(Bierman, 1998)

Figure II-3. Structure of an LED Typically Used for Illumination



Source: (Bullough, 2003)

The ambition to create truly white LEDs for use in general illumination applications is a challenge and accordingly, has been dubbed the "Holy Grail" by the SSL industry. Today, most of the so-called "white" LEDs on the market are made by combining a blue LED chip with a phosphorus coating. The phophors absorbs some of the blue light emitted and down convert it to a yellow light: the mix of blue and yellow light create a rough approximation of white light. The human eye however, perceives this combination of yellow and blue light as more of a "dirty" white, than the familiar warm glow of an incandescent lamp (Martin, 2001).

There are several other technology pathways available to create a better white LED, including coupling a UV LED chip with several phosphors, as well as placing the three primary color LEDs (blue, red, and green) close enough so their colors mix and appear white. More recently, technology developments using UV light with nanosized quantum dots appears to be a highly promising option for creating white SSL (Sandia National Laboratory, 2003).

One of the most well known lighting technologies – the incandescent bulb which Thomas Edison developed in the late 1800s – today remains the most pervasive source of light in residential settings. These lamps operate extremely inefficiently by passing electricity through a metal tungsten filament, with only approximately 5-10% of the energy converted to light and the rest dissipated as heat. Incandescent lamps, along with other sources of light more commonly used in commercial and industrial settings (such as fluorescent and high intensity discharge lamps), are expected to begin to be gradually replaced over the next few decades by SSL. However SSL must first surmount a number of technical challenges. These include reducing the cost and improving the performance of SSL technology, allowing it to be cost-competitive with existing technologies in the general illumination market.[12] Furthermore, there will be challenges on the road to wide-spread adoption including the creation of common standards and a supporting infrastructure for SSL technology, as well as consumer sensitivity to the higher upfront capital cost of SSL.

The performance of SSL is expected in time to become far superior to that of conventional lighting technologies. Experts in the field anticipate that SSL will eventually become highly efficient – on the order of 150-200 lumens per watt (lm/W), which is approximately ten times more efficient than incandescent lighting – typically 15-20 lm/W, and twice as efficient as fluorescent lighting – typically 60-85 lm/W (DOE, 2003b). Solid-state lighting is also expected to eventually achieve a much longer lifetime than conventional lighting – up to approximately 100,000 hrs, as opposed to incandescent lighting which on average has a lifetime of 1,000 hr, and fluorescent lighting whose lifetime ranges from 15,000-20,0000 hr. Other favorable characteristics of SSL include its durability, compactness, and dimmability, as well as the potential to change the color of light through the flip of a switch. These options could open up a new range of creative architectural possibilities. However, presently using LEDs for general illumination comes at a very high cost. Currently, costs for SSL in dollars per lumen are a full two orders of magnitude above conventional lighting technologies. Furthermore, efficacies presently border only around 20-30 lm/W for commercially available devices, although laboratory prototypes have reached close to the efficacy of fluorescent lamps. Color quality and stability over the lifetime of SSL are two other essential attributes which must be competitive

[12] Competitive on a life-cycle basis which includes a combined cost of the upfront capitol cost and the costs of operation (*e.g.*, the cost of the electricity consumed).

with conventional technologies in order for SSL to become widely used in the general illumination market.

Since 1999 there has been a series of collaborative activities between government and industry to study and promote the potential of SSL as future energy-efficient and cost-saving technology in the general lighting sector. In 2001 the first technology roadmap for SSL was developed jointly by the DOE Building Technologies Program and the Optoelectronics Industry Development Association (OIDA), to accelerate the development and commercialization of SSL for general illumination ("The Promise of Solid State Lighting for General Illumination: Light Emitting Diodes (LEDs) and Organic Light Emitting Diodes (OLEDs)," 2001). [13] This published roadmap provides a highly optimistic outlook for SSL, and estimates that by 2025 SSL could reduce the global amount of energy consumed for lighting by 50%.

However the roadmap also discussed numerous and significant technical hurdles which must be overcome before this technology is able to come to fruition. The roadmap was subsequently updated in 2002 at which point the experts in the SSL community came together to further focus their vision and define key technical challenges which must be address for general illumination SSL to become a reality (Tsao, 2002). In this roadmap, performance and cost targets for SSL were established through the year 2020. These roadmap targets with updated modifications from Tsao are shown below in Table II-1. On the right hand side of the graph, performance attributes and costs of conventional lighting technologies are provided for comparison. The performance improvements and cost reductions necessary for LED-SSL to be competitive with traditional technologies are far from trivial, yet industry experts are optimistic that they are

[13] Both organic and inorganic solid-state lighting technologies were included in this roadmap.

feasible. However, it should kept in mind that these scenarios below were established with the expectation that a significant national investment in SSL would begin in 2002; the scenario could play out differently under an alternate investment scenario (Tsao, 2004).

Table II-1. Roadmap Targets for SSL-LED Technology in Comparison to Conventional Lighting Technologies

Lamp Targets	SSL-LED 2002	SSL-LED 2007	SSL-LED 2012	SSL-LED 2020	Incandescent	Fluorescent	HID
Luminous Efficiency (lm/W)	20	75	150	200	16	85	90
Lifetime (hr)	20,000	20,000	100,000	100,000	1,000	10,000	20,000
Flux (lm/lamp)	25	200	1,000	1,500	1,200	3,400	36,000
Input Power (W/lamp)	1.3	2.7	6.7	7.5	75.0	40.0	400.0
Lamp Cost (US $/klm)	200.0	20.0	5.0	2.0	0.4	1.5	1.0
Lamp Cost (US $/lamp)	5.0	4.0	5.0	3.0	0.5	5.0	35.0
Color Rendering Index (CRI)	70	80	80	80	100	75	80
Lighting Markets Penetrated	Low-Flux	Incandescent	Fluorescent	All			

Source: Data from (Tsao, 2004, 2002)
Note: The costs are in "street costs," estimated approximately 2 times higher than the original equipment manufacture costs.

A workshop was convened by the National Academies in 2001 with participants from industry, academia and government, to explore the potential of SSL (NRC, 2002). The report addressed current and potential applications, current and potential operational advantages, the potential advantages of widespread use of this technology, and the core challenges faced by industry in bringing this technology to market. Three core challenge areas that were addressed in this report include: remaining technical hurdles, the need to develop the new lighting infrastructure, and the psychological barriers to market acceptance.

3.2 Drivers & Challenges

There are a number of important drivers propelling the development and diffusion of LED-SSL into the general illumination market. These drivers are discussed below and have been grouped into six broad categories: environmental, performance and human interaction, safety, economic, energy, and potential spin-offs.

Environmental. One of the most important environmental benefits of SSL is its potential to yield significant energy savings, and hence reduce CO_2 emissions. Furthermore, SSL contains no mercury, a toxin that is found in all fluorescent and many HID lighting technologies. Finally, the relative compactness and longevity of SSL compared with conventional technologies, offers the potential to reduce the waste stream.

Performance and Human Interaction. SSL has the potential to create a new lighting culture, significantly changing how we use and interact with light (Tsao, 2002). This technology offers an array of exciting and new innovative architectural possibilities including the ability to continuously vary the color of light, the ability to dim the lighting without loosing efficiency, and the potential to design unobtrusive and architecturally blended luminaires and fixtures. It has been hypothesized that SSL might even have a positive impact on the level of human comfort and productivity in the workplace, which, in it and of itself, could provide significant economic benefits (Tsao, 2002). For example, a dynamic SSL system could allow the intensity and color of the light to be changed to suit the particular user and/or their mood or level of activity. Balancing the ratio between task (direct) lighting and diffuse (indirect) lighting could also have an impact on the human interaction with lighting.

Safety. Safety is an important consideration for new technologies. One inherent advantage of LEDs is that they are low power devices. Since LEDs operate at low voltages, they can provide simpler installation and a higher level of safety for the installer (Ton, Foster, Calwell, & Conway, 2003).

Economic. The energy-savings potential estimated by the DOE (2003b) market penetration model reveals that end-use customers will save approximately $130 billion dollars (undiscounted), cumulatively between 2005 and 2025 on their electricity bills from the development and adoption of efficient SSL. Furthermore, there is an important national economic and innovation advantage of creating a strong SSL industry within the U.S. (Romig, 2002).

Energy. Solid-state lighting has the potential to deliver improved lighting service at a fraction of the energy required by conventional lighting technologies. In the U.S. as well as other developed countries throughout the world, artificial lighting has become an essential component of modern life. The transition from conventional technologies to SSL offers the potential to dramatically reduce the energy consumed for lighting. One important benefit of SSL is that its higher efficiency can lessen the strain on the electricity grid during peak hours of demand because lighting is a peak-load consumer of electricity.

Potential Spin-offs. The materials systems found in LED chips are compound semiconductor materials such as aluminum gallium indium nitride (AlGaInN). These materials systems are also used in a number of technologies critical to national security (Tsao, 2002). For instance, such technologies include high-powered electronics for wireless and radar applications, solar-blind detectors used to detect missile launches, and as UV light sources for detecting biological and chemical agents.

There are a number of challenges to be overcome before SSL expands from niche applications into being widely used for general illumination. These challenges, sometimes also referred to as "barriers," have been identified and grouped into three categories: technical, infrastructure and market barriers.

Technical. There are a host of technical barriers that must be surmounted before a new lighting "paradigm" based on SSL comes to fruition. The SSL research and development (R&D) initiative by the DOE is currently focused in six critical technical areas: quantum efficiency, packaging, longevity, infrastructure, stability and control, and cost reduction (DOE, 2004). A detailed discussion of the technical barriers can be found in (Tsao, 2002).

Infrastructure. It is uncertain as to whether future LED-SSL devices will be direct replacements for existing lighting sockets or whether an entirely new lighting infrastructure will be created, independent of the "bulb culture" (Tsao, 2002). On one hand, accelerating near-term adoption could be accomplished by making LED-SSL devices that come with the necessary circuitry and are able to fit directly into existing sockets. In fact a few such Edison-socket LED bulbs are commercially available today.[14] In addition, many of the energy-savings estimates have been predicated on the assumption that SSL will be able to be used in existing sockets (DOE, 2001, 2003b;

[14] See http://ledmuseum.home.att.net/ for a wide overview and review of currently available LED products.

Drenner, 2001). Energy-savings in general illumination lighting over the next two decades could be significantly lower if LED-SSL is only available for new building construction or large lighting retrofit projects. On the other hand, creating a new lighting infrastructure based on the unique and innovative characteristics of SSL could be a critical driver of SSL success in the general illumination market.

The revolutionary nature of LED-SSL in the lighting market will necessitate that accompanying codes and standards be developed alongside this new technology. New guidelines for installation and product codes and certifications (for instance the "UL" label provided by the Underwriters Laboratory) must be developed.[15]

Unless new metrics are developed and embraced by the lighting community, it is likely that final users will compare LEDs to conventional lighting technologies as well to other LEDs, using CRI and CCT. Because these metrics are not well suited for LEDs, it is possible that using them could actually impede the diffusion of LED-SSL. Standardizing other metrics for LEDs (such as the rated lifetime of the LED-SSL device) will be important so that end-users can comparatively evaluate LED-SSL products from different manufactures, as well as compare LED-SSL to traditional lighting technologies.

Market. Since LED-SSL promises to be a highly innovative and energy-efficient way of providing lighting service, it will likely be a disruptive technology in the existing general illumination market that is dominated by incandescent, fluorescent and HID lamps.

[15] The Underwriters Laboratory has evaluated LED lighting systems and components for applications such as exit signs, traffic lights, and general lighting. For more information see: http://www.ul.com/lighting/led.html

However, displacing older lighting technologies is likely to be challenging, in part because of the vertically integrated structure of the mature lamp industry. Many of these industries are not set up to buy their components from third parties, and none of them currently manufacture the LED chips that are the heart of LED-SSL. Furthermore, many end-users now require highly specialized lighting products, which have resulted in a highly fragmentized lighting industry.

In January 2004, a conference entitled “LEDs: Meeting the Design and Performance Challenges” was held.(Whitaker, 2004) This gathering was slated towards lighting designers and end-users in the industry, but also brought in some LED manufactures. The meeting highlighted a disconnect between these two communities, revealing that more communication between them will be important for realizing the potential of LED-SSL. Important issues voiced by lighting designers included uncertainty on how to incorporate LEDs into their products and designs, and a difficulty at computing the costs and benefits of using LEDs over conventional technologies, particularly because of a lack of standardization.

Finally, the high upfront capital cost (on a $/klm basis) of SSL when compared to incumbent lighting technologies will be a significant barrier for the adoption of SSL. (See Table II-1) Currently, LED-SSL is penetrating niche markets (*e.g.,* traffic signals, exit signs, and automobile lighting) in which the inherent characteristics of the technology (*e.g.,* its monochromatic nature, longevity, ruggedness, or compactness) can provide a unique advantage over traditional lighting technologies. Eventually as the performance improves and costs are reduced, SSL will be able to compete with conventional technologies on a simple payback, or life-cycle costing basis.

3.3 DOE Market Penetration Model

Estimates for the future global energy savings achievable from SSL have been as optimistic as a 50% reduction by 2025, which would in turn decrease total electricity consumption by about 10% (Tsao, 2004). In the U.S., a recent analysis by the DOE (2003b)using a SSL market penetration model found that by 2025, SSL in general illumination applications could reduce the amount of electricity needed for lighting by 33%. This analysis was based on a spreadsheet model, which simulated consumer lighting purchasing decisions over a twenty year time period in order to estimate the market penetration of SSL and the subsequent energy savings.[16] Below is a brief description of the DOE model. For a complete overview of the methodology used in constructing the model, the report is available from the DOE website.[17] Much of the basic framework used to create the DOE model was carried over to build the STELLA model used in this thesis. However, there are several important distinctions which will be further discussed in the following chapter when the modeling methodology is described.

[16] There are several other models and reports what have estimated the energy savings potential of solid-state lighting (see Drenner, 2001 and DOE, 2001). The DOE (2003b) model is believed to be the most recent and detailed model available.
[17] This report is found on the DOE Office of Energy Efficiency and Renewable Energy, Building Technologies Program, accessible at http://www.netl.doe.gov/ssl/

DOE Model Description

The projected lighting demand is based on new construction estimates used in the National Energy Modeling System (NEMS) and the Annual Energy Outlook (2003). The DOE *U.S. Lighting Market Characterization* report (2002) is used to provide the baseline inventory of installed lighting technologies and their characteristics. The market includes four sectors: residential, commercial, industrial and outdoor stationary. The inventory of the lighting stock is broken down into four bins by color rendering index (CRI) value.[18] The CRI is used as a proxy for the lighting quality required for a certain application and the four bins created include: low, medium, high and very high CRI.

The model is constructed to simulate the purchasing decision of new lighting technologies. When purchasing decisions are made, there is market turnover in which SSL has the potential to be adopted. The market turnover occurs via three different routes: new installation (new construction), replacement lamps, and retrofitted lighting systems. The performance and costs of conventional technologies were projected to improve minimally, on a linear basis. The SSL performance improvements (efficacy and lifetime) and cost reductions were developed in consultation with industry experts for two scenarios: an accelerated scenario ($100 million annual national investment) and a moderate scenario ($50 million annual national investment). The SSL technology improvements over time followed an s-curve, in which first exponential progress gives way to linear improvements, and finally the curve levels off as the technology asymptotically reaches its maturity. It is important to note that for simplification purposes an aggregate set of SSL curves, which encompass both LEDs and OLEDs for SSL, were developed and used in the model.

Due to the competition from SSL, the conventional lighting technologies are assumed to improve modestly, but the improvement potential is limited because they are relatively mature technologies. Three different conventional technology improvement scenarios are given: low, medium and high baseline, although the medium baseline scenario is used as the default throughout the analysis.

The SSL competes against the conventional lighting technologies, and the model awards market share to various technologies based on simple-payback. Simple payback is the ratio of the first year incremental capital cost to the first year incremental savings, expressed in years. Using market penetration curves for simple payback developed by Arthur D. Little Inc., the number of year's payback determines the percentage market share awarded to SSL. For instance, in the commercial sector if the payback period is two years SSL will gain a 30% market penetration, while if instead the payback period is four years, the market penetration will only be about 8%.

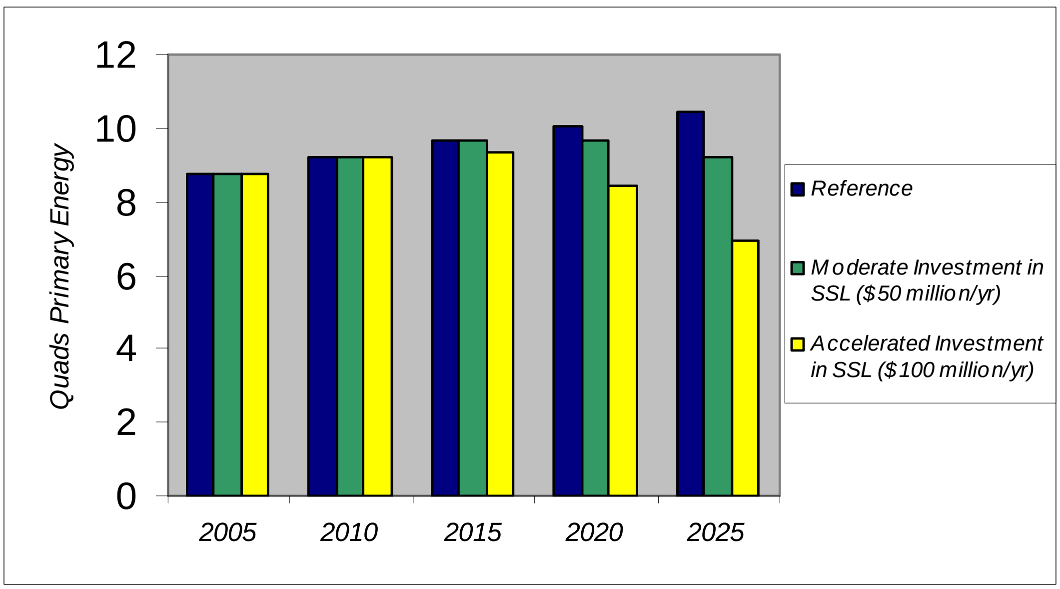
Source: (DOE, 2003b)

Figure II-4 captures the results of the aggregate energy-saving possible between 2005 and 2025, in the three scenarios used in the model. In the reference scenario, energy consumption for lighting is projected out to 2025 assuming that there is no SSL market penetration. The conventional lighting technologies are assumed to improve only modestly; the performance

[18] The CRI of a lamp is a measure of how surface colors appear when illuminated by the lamp, in comparison to how they appear when they are illuminated by some reference light source of the same color temperature.

improvements and cost reductions are minimal because it is assumed that these technologies are relatively mature. The modest investment assumes that industry and government work together to develop SSL, but with only a modest investment ($50 million per year), the technology is not developed quickly enough to yield significant energy savings. In the accelerated scenario, the national investment is twice that of the modest investment ($100 million per year). It is assumed that this higher level of R&D is able to achieve better SSL performance (efficacy and lifetime) and lower costs, and thus this scenario yields the most significant energy savings.

Figure II-4. U.S. Primary Energy Consumption – Three Scenarios



Source: (DOE, 2003b)

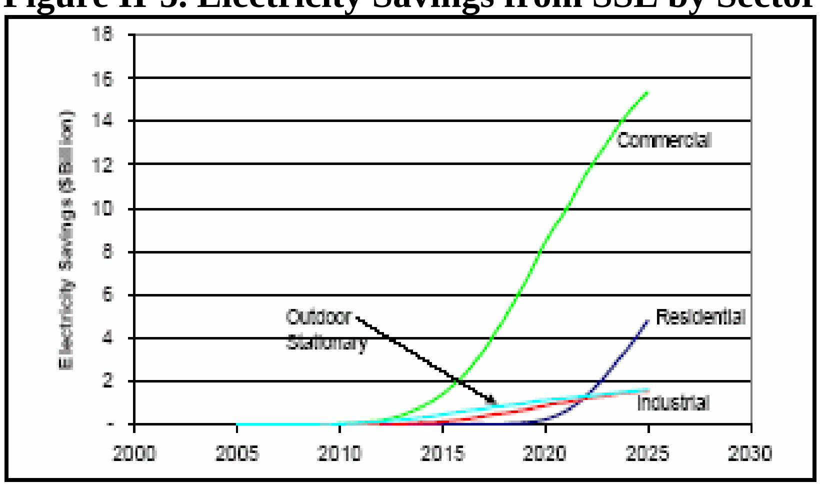
In the reference scenario seen in Figure II-4, lighting consumes 10.47 quads of primary energy in 2025. The moderate investment scenario saves 1.23 quads in 2025, or approximately 12% from the reference scenario. The accelerated investment scenario yields a higher energy savings of 3.51 quads, or approximately 33%.[19] Cumulatively between 2005 and 2025, the modest

[19] The uncertainly given for the moderate investment scenario is +/- 0.2 quads, and for the accelerated investment scenario is +/- 0.5 quads.

investment scenario saves 5.44 quads of primary energy, while the accelerated investment scenario saves 19.9 quads.

The total undiscounted savings across all sectors of the economy for the accelerated investment scenario is approximately $130 billion dollars. When these savings are broken down by sector as depicted below in Figure II-5, the commercial sector would see the bulk (72%) of these savings. In this analysis, by 2025 SSL has penetrated into all four of the market sectors. However, the majority of the energy savings accrue from replacing inefficient incandescent lighting in the residential and commercial sectors.   It is also interesting to note that the commercial and the outdoor stationary sectors are shown to be the earliest adopter of this SSL technology, with adoption beginning in roughly 2012. Penetration into the residential sector does not begin until considerably later in 2019.

Figure II-5. Electricity Savings from SSL by Sector



Source: (DOE, 2003b)

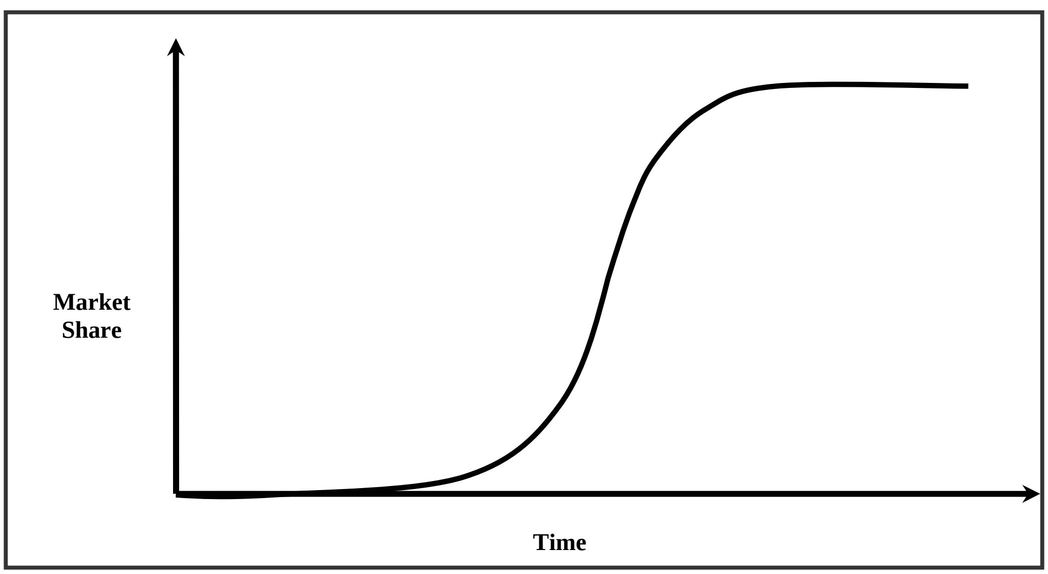
The future market penetration potential of SSL in this model is driven largely by the technological characteristics of SSL which in turn determine the economics of SSL in terms of initial price, efficacy, lifetime, and operational costs (DOE, 2003b).   However, while economics will be a very important factor in the penetration of SSL into the lighting market, it is critical to remember that it is not the only factor. The lighting market is a complex entity (Vorsatz et al., 1997). Whether or not consumers purchase SSL will also depend on their awareness of this new technology and its advantages, the aesthetic appeal of this new lighting, and if they are able to conveniently purchase it. Furthermore, in organizations there is a combination of cultural, institutional, macro-social/economic and technical factors that can shape the behavior of firms (Lutzenhiser, 1994), which would in turn affect the lighting purchasing decisions made in the commercial building sector.

Despite the rapid pace of technology advancement in SSL, currently the technology is too immature for use in most general illumination applications. Furthermore, although SSL appears to be a highly promising technology it is important to keep in mind that there are a number of efficient and cost-effective lighting technologies as well as energy-savings lighting designs and controls that are currently available on the market. If adopted, these too could result in significant energy savings. Atkinson et al. (1992) determined that if cost-effective lighting technologies already on the market were installed, electricity consumption for commercial interior lighting could be reduced as much as 50-60%, and residential interior and exterior electricity consumption could be reduced by as much as 20-3%. Hence, while SSL efficacies of 150-200 lm/W have the technical potential to be twice as efficient as fluorescent lighting and up to ten times as efficient as incandescent lighting, there is reason to be cautious of highly optimistic estimates of national energy-savings. To understand the energy-efficiency potential of SSL one needs to take into account things such as: the gradual diffusion of all new technologies, barriers which are often common to energy-efficient technologies, as well as the drivers and challenges that will shape the development and market penetration of SSL. The gradual diffusion process that all new technologies experience is discussed in greater length in the following section.

4. Technology Diffusion

The diffusion of innovation was defined by Everett Rogers as “the process by which an innovation is communicated though certain channels over time among the members of a social system” (Rogers, 1995). Most innovations have a rate of adoption which follows an s-shaped curve, as seen below in Figure II-6 (Rogers, 1995). That is, early on in the introduction of a new technology there are relatively few adopters. As time progresses, more and more people begin to adopt the technology and the curve rapidly rises. Eventually, the number of new adopters declines and the curve asymptotically reaches market saturation.

Figure II-6. The S-Curve of Diffusion



4.1 Models of Diffusion

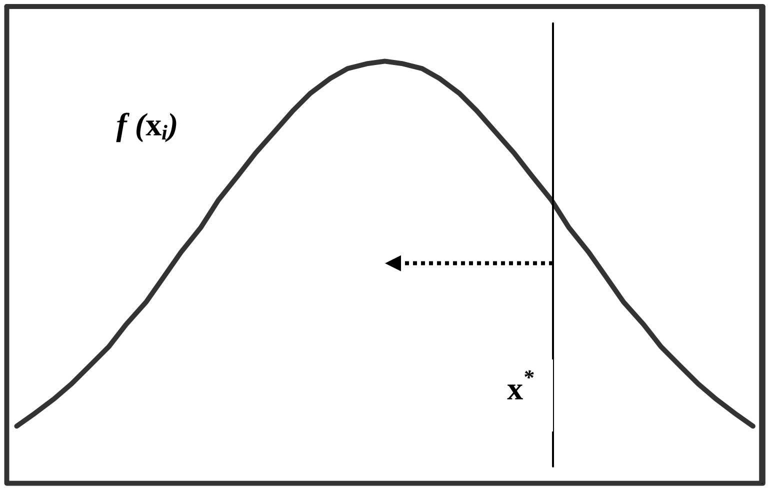
Research on the diffusion of innovations has crossed a multitude of disciplines, including sociology, anthropology, education, public health, marketing and economics (Rogers, 1995). Geroski (2000) surveys the literature on alternative models of technology diffusion. Most of the conceptual models have been constructed to explain the stylized fact that the usage of a new technology over time follows an s-shaped, or 'sigmoid' curve over time.

Why does the usage of a new technology follow this s-shaped curve over time? Empirical studies, beginning with the pioneering case study of the diffusion of hybrid corn by Griliches (1957) have consistently found that the pattern of technology diffusion follows the shape of an s-curve. Different models have been created to account for this diffusion pattern and each of these models embody a distinct, but often complementary, explanation for the gradual diffusion. Geroski (2000) cites that the epidemic model is the most commonly used. This model is predicated upon the spread of information about a new technology throughout society. Just as an infectious disease can be transmitted throughout population when "infected" individuals come into contact with healthy individuals, the diffusion of a new technology can be likened to technology "users" spreading information about the new innovation to non-users. The information about a new innovation is communicated though social networks.

However Geroski (2000) makes the distinction between pure information and information about a new technology. He reasons that pure information can be passed on to many people from a central source, but actual technology adoption usually takes longer to spread than pure information – for instance – a breaking new story. This is because there is a certain kind of information that can only build up from using a technology; this tacit knowledge is transmitted from person to person, much like an infection disease can be passed on from an "infected" individual to those that are healthy. Hence there are two distinct paths that information can be transferred: from a central source, and by word-of-month. Despite that the epidemic model is commonly used, Geroski (2000) explains that this model begins to break down when one considers that the adoption of a new technology does not only involve information about the technology, but also persuasion to adopt the technology.

The leading alternative to the epidemic model is the probit model, which attempts to model the choice made to adopt a technology by an individual decision maker. Geroski (2000) provides the following simple explanation of how this model works. Consider that there is a population of individuals that differ in some characteristic x_i, and that they are distributed across some population in the normal distribution function $f(x_i)$ pictured in Figure II-7.   Suppose that individuals with levels of x_i larger than x* chose to adopt, but the others don't. If x* was to sweep from right to left at a constant rate, then one can imagine the rate of adoption will gradually rise and then fall, creating an s-shaped curve.   In this case, the shape of the s-curve would depend on how the x_i are distributed, and the rate at which x* changes over time. The variable of x_i might represent for instance, firm size.

Figure II-7. Normal Distribution of Variable (x_i)



Suppliers on the other hand are agents that can affect the costs and benefits associated with a new technology, and thereby affect how x* changes over time (Geroski, 2000). How well these suppliers take into account the preferences and needs of their potential customer base, their pricing and servicing policies for the technology, and the flow of information (*e.g.* marketing) they facilitate about the technology are all determinants of the rate of diffusion. Technological expectations are also likely to influence the rate of diffusion: when expectations are high that there will be a near-term improvements in the technology (either the old or the new), diffusion is likely to be slower (Geroski, 2000).

Geroski (2000) cites a number of additional factors that can drive diffusion including: learning and search costs, switching costs, and opportunity costs. Learning and search costs pertain to the uncertainties that surround the decision to adopt a new technology. Initially, it is oftentimes difficult to gauge the benefits of a new technology with high certainty. But over time, information becomes more readily available and depending on how quickly the firms update their old information (learning), they can reassess their decision to adopt the technology.

Switching costs can affect the decision to adopt a new technology, because there are a number of different factors that might lock-in an existing technology. Finally, there could be opportunity costs which are created by previous investments in technology that hasn't fully depreciated. For example, if a firm purchased new computers only two years ago, they would be less likely to purchase the latest computer model than a firm using six-year old computers.

Innovations can diffuse rapidly throughout society, in which case they have a steep rate of adoption. On the other hand, innovations can also diffuse more slowly, and in this case the slope of the s-curve is less steep. Either way, it is important to note that in neither case is the diffusion of a new technology instantaneous. The period from when the first user adopts a new technology until the technology is used by (for example) 90% of the market, can extend anywhere from five to fifty years (Mansfield, 1968).

Case studies have historically been used to empirically investigate the determinants of the diffusion process. For example, the early work of Griliches (1957) analyzed the diffusion of a new hybrid corn variety and found that the rate of diffusion was the most rapid in geographic areas in which the economic return to adopting the hybrid corn was the greatest. Mansfield (1968) found that the rate of diffusion was also dependent on the size of the adopting firm, the absolute magnitude of the investment and the perceived riskiness of the new technology. The diffusion process has also been studied from the view of why certain firms adopt early and others adopt late. Differences among potential users does not necessary have to be based on the size of the adopting firm; rather the crucial component is that potential adopters be heterogeneous across some dimension that will affect the value of the innovation, and hence their adoption decision (Jaffe & Stavins, 1991).

4.2 Justification for Policy Intervention

The process of technological change can be characterized by the Schumpeterian trilogy: *invention* – the generation of a new idea; *innovation* – the development of those ideas into a marketable technology; and *diffusion* – the spread of the technology across its potential market (Stoneman & Diederen, 1994). The time path of adoption of an innovation is the result of interacting supply and demand factors. Policy initiatives to affect the process of technological change have predominantly focused on the first two processes, invention and innovation, by focusing on the science and R&D end of the spectrum. Both public policy and research have historically tended to neglect the diffusion process (Jaffe & Stavins, 1991; Stoneman & Diederen, 1994) However more recently there has been a greater focus on diffusion policies for energy equipment, because of concerns surrounding global climate change (Jaffe & Stavins, 1994a). Policies designed specifically to promote and accelerate the diffusion of energy-efficient equipment are discussed later in this chapter.

Stoneman & Diederen (1994) provide an overview on why policy intervention into the diffusion process may be desirable, and if so, what form it might take. Assuming that the development path of a new technology is predetermined and fixed,[20] Stoneman & Diederen (1994) state that the optimal path of technology diffusion can be thought of as "that path on which at any point in time the social benefit to be gained from the adoption of the technology by the marginal user in

[20] However, there is a feedback loop in which profits generated early on in the diffusion path are fed back into R&D, which then improve production processes and the technology itself. This feedback loop considerably complicates the specification of this welfare optimal diffusion path (Stoneman & Diederen, 1994).

time *t* (as opposed to earlier or later) will equal the marginal social cost of producing the capital goods that embody that technology in time *t*." In other words, a technology's optimal path of diffusion over time can be thought of as a one in which the net social benefits are maximized at every point in time.

This definition of a welfare optimal path of diffusion implies that the actual rate of diffusion can deviate from it in two ways: the actual diffusion can either be too fast, or too slow from the optimal path. This is generally caused by what is known as a market failure. Three primary types of market failures can affect the diffusion process: imperfect information, market power and externalities (Stoneman & Diederen, 1994).

First, the efficiency of a market for a new technology is constrained by information asymmetries and deficiencies, more so than other markets. This is because at a fundamental level, technology can be thought of as information and markets for information are notorious for their imperfectness (Arrow, 1962). The information about a new technology could be imperfect because the characteristics or costs of a new technology are not well known, or information that supplies future expectations (for example the future performance or cost) of a new technology might be inaccurate. Accordingly, Stoneman & Diederen (1994) suggest that policy intervention in terms of providing information is desirable up to the point at which the marginal social cost of supplying the information is equal to the marginal social benefit gained from the information.
In addition to providing information, the government might also correct a market failure stemming from imperfect information is by either shifting the burden of risk to the government,

or by reducing uncertainty in the market by “creating” information in the form of technical standards (Stoneman & Diederen, 1994).

The second main market failures identified by Stoneman & Diederen (1994) is market power, which can apply to either the supplying industry or to the using industry. While the literature does not elucidate which market structure will always generate optimal diffusion, in general, a view widely held is a monopoly on the supply side will slow the diffusion path (Stoneman & Diederen, 1994).

Stoneman & Diederen (1994) discuss both positive and negative externalities as the third major market failure. Negative externalities can occur when the adoption of a technology by one firm negatively affects the profits of another firm. For instance, if a new technology is adopted by one firm that subsequently give it an advantage over competing firms, these competitors will be negatively affected. Energy-use also creates negative externalities because of the CO_2 emissions and other pollutants that are created through energy production and use. Positive externalities of technology diffusion can also occur. For example, a firm’s decision to adopt a new technology can create a flow of information that spills over other firms. In other instances, as in the case with network technologies (*e.g.*, telephones or fax machines), the benefits of adopting a technology can increase with the number of users.   Finally, other positive externalities can occur through private sector R&D, new job creation, and technology spill-overs that enhance national security.

4.3 What Can Government Do?

Although there may be a limited number of policies in use aimed specifically at tuning the rate of diffusion, there are a considerable number of public policies that have other primary objectives but also have a major impact on the diffusion process (Stoneman & Diederen, 1994). Such policies include R&D policies, industrial policies, education policies, infrastructure and transportation policies, environmental protection, accounting rules such as depreciation. Nonetheless, disappointment over the slow diffusion rates of new energy technologies, has generated interest in the determinants of the rate of technology diffusion (Jaffe & Stavins, 1991). Designing effective policies to accelerate the diffusion process requires an understanding of the process itself.

The spread of information is central to the epidemic model, and therefore improving the mechanism through which information spreads in the economy is one way in which public policy can directly affect the diffusion process (Geroski, 2000). Policymakers can accomplish this by becoming the central source of objective information about a new technology. Policymakers can also identify key actors with an stake in a new technology, and either provide them with subsidies or bring these actors together in a forum setting where they can communicate with each other thereby enhancing the epidemic effect.

Government procurement where the government leverages its significant purchasing power to become an early user of a new technology is another policy that can accelerate diffusion. Governments are large, generally well informed and relative cost insensitive, and can therefore be important agents for diffusion (Geroski, 2000). In addition, public policies such as standard setting and direct regulation can also promote the diffusion of new technologies.

A probit model was used in the DOE SSL market penetration models, to simulate the decision making process that guided the diffusion of SSL (DOE, 2001, 2003b). These models were based on a predefined simple payback period: a certain percentage of the market would adopt SSL if the payback period from the investment was below a certain threshold payback period measured in years. However, Geroski (2000) points out, one weakness of probit models is that they don't account for the gradual amount of information available to users which builds up, leaving out the important social epidemic aspect of innovation diffusion.

This research forges a link between the strengths of these two models. By building a model that simulates the decision making processes according to the rules of simple payback, the diffusion of SSL is based on a decision process on a micro-economic level according to simple payback either to adopt SSL or not adopt SSL. The advantage of building this model in STELLA as opposed to a spreadsheet is that using STELLA software allows the builder to think through the links between numerous variables which affect the diffusion process. This allows the model to be built in such a way that it takes into account the dynamics which occur due to the epidemic effect, such as spread of information and awareness as more and more users adopt SSL, which in turn is likely to influence more consumers to adopt the technology.

5. Energy-Efficiency & Lighting

There has been a substantial body of literature on the so-called "energy-efficiency gap"; that is, a widespread gap between the energy-efficiency of products which consumers buy and use, and the apparently cost-effective level of energy-efficiency which is available on the market. In this section the energy-efficiency gap will be further examined. Further focus is placed on the commercial building sector and the energy-efficiency gap as it pertains specifically to lighting technologies. Finally, the chapter concludes with why public policy should be considered to promote and accelerate the diffusion of energy-efficient lighting technologies in the commercial building sector.

5.1 The "Energy-Efficiency Gap"

In the ample collection of literature available that focuses on the energy-efficiency gap, much of the discussion has centered around the posit that consumers seem to be using high implicit discount rates when they evaluate investments in energy-using technologies These implicit discount rates are much higher than other interest rates in the economy; but the real question is *why* are these rates are so high for consumers? Do these high discount rates truly represent real costs to the consumer or are the result of a market failure? When high discount rates represent real costs and not market failures, Jaffe & Stavins (1994b) argue that public policy intervention should not be used. On the other hand, if the discount rates are attributed to market failures, these failures could potentially be amenable to public policy.

There have been a number of documented cases in which the consumers chose not to purchase highly-efficient and economical energy technologies (Brown, 2001). Brown (2001) articulates a number of the market failures and barriers which inhibit consumer investment in energy-efficient technologies. Market failures occur when there are flaws in the way the market operates. Brown cites examples of market failures including misplaced incentives; distorted fiscal and regulatory policies; unpriced costs; unpriced public goods including education, training and technological advances; and insufficient and inaccurate information. Brown then goes on to differentiate between market barriers from market failures. She argues that market barriers are not market failures per se, but nevertheless contribute to the slow diffusion and adoption of energy-efficient innovations. Market barriers according to Brown (2001) include the low priority of energy issues among the public, capitol market barriers, and incomplete markets for energy-efficiency.

To determine the right measure of the energy-efficiency gap, Jaffe & Stavins (1994b) cite that it's necessary to understand and draw a distinction between market failures and non-market failures. (These non-market failures are similar to what Brown (2001) terms market barriers.) According to Jaffe and Stavins, both market failure and non-market failures contribute to explaining the so-called "paradox" of the gradual diffusion of energy-efficient technologies (also referred to above as the energy-efficiency gap). It has been called a "paradox" because technologies which are energy-efficient and appear to be cost-effective are only gradually adopted. Jaffe & Stavins (1994b) however correctly point out that the notion that a paradox exists for energy-efficient technologies is somewhat diluted, when one takes into account that all new technologies experience only gradual diffusion.

Jaffe & Stavins (1994b) go on to list several specific sources of market failures that may affect the adoption rates of energy-efficient technologies: information which has public good attributes tends to be underprovided in the market; the act of adopting a technology creates a positive externality for which the adopter is usually not compensated; and the principle-agent problem in which the person purchasing the technology is not the party that pays the energy bills. For instance, consider an example of the principle-agent problem: If a landlord pays the electricity bill while a renter purchases the light bulbs, the renter has no incentive to purchase a more energy-efficient (and more expensive) CFL over the incandescent bulb, because the renter doesn't pay the electricity bill and will therefore never recoup the savings from higher level of energy-efficiency. The principle-agent problem is an example of what Brown (2001) referred to as misplaced incentives.

Non-market failures are said to explain why the observed behavior is actually *optimal* from the point of view of energy users. Jaffe & Stavins (1994b) discuss examples of non-market failures that represent additional (and real) costs for consumer. These costs include: uncertainty about future energy prices combined with the irreversible nature of the technology investment; qualitative attributes of energy-efficient technologies that make them less desirable than existing technologies; and the heterogeneous nature of the population (*e.g.*, although the technology might be cost-effective for the average consumer it won't be for every consumer).

5.2 The Building Sector

Each end sector is unique in its assortment of market failures and barriers that prevent the use of cleaner energy technologies (Brown, 2001). This is largely because each sector has a different market structure for delivering new technologies. In the residential and commercial building sector, this market structure is made up of building contractors, engineering firms, and architects and designers, while in the transportation sector the market structure is dominated by a few large manufacturers. Because the market structure in the residential and commercial sectors is made up of multiple actors, yet another variation of the principle-agent problem (discussed earlier for the case of the landlord and renter) can arise.

In the building sector in particular, a unique barrier to greater energy-efficiency is the information gap that prevents the energy-efficient features of a building to be reflected in the real estate price (Brown, 2001). There is also a limited flexibility to change in response to fuel price, which is partially limited by the lifetime of equipment. For instance, shorter technology lifetimes will create quicker turn over and thus more opportunities to respond to the price signals from energy costs. Furthermore, different sectors of the economy have varying R&D capacities to respond to market signals and energy prices. While many industries on average spend about 3.5% of their sales on R&D, it is estimated that the construction industry on the other hand spends less than 0.2% (Brown, 2001).

While most of the discussion to this point has concentrated on assessing energy-efficiency from either a technologist or economic viewpoint, there have been a number of studies in the social sciences which have focused on the factors which affect energy use (Poortinga, Steg, Vlek, & Wiersma, 2003). This work has involved studies which look at the social and psychological factors related to energy-saving behavior, social processes, as well as the effect of information and feedback on energy-saving behaviors. The social sciences in particular can help to illuminate behaviors and social processes which are to a large extent ignored in economic models of energy use and technology adoption (Stern, 1986). For instance, Lutzenhiser (1994) focuses on the role of organizational networks in the shaping the diffusion process of an innovation

(Lutzenhiser, 1994). In this work, she emphasizes the role that industry organizations have on impeding energy-efficiency innovation in the housing sector.

5.3 Lighting Technologies

In the lighting sector, there has been research which has explored the hurdles which energy-efficient lighting technologies face in the marketplace. Hurdles that contribute to the slow diffusion of new lighting technologies include the crudeness of the early technology and the comparative advantages held by older entrenched technologies such as increasing returns to scale and cumulative learning (Menanteau & Lefebvre, 2000). In particular, when compact fluorescent lamps (CFLs) were introduced in the early 1980s, one of the most important barriers that CFLs faced was their high upfront cost. This high capital cost served as a psychological barrier to consumers. Furthermore, many residential consumers were not used to thinking in terms of life-cycle costing and had very high implicit discount rates (Menanteau & Lefebvre, 2000).

For the lighting market in particular, previous case studies of markets for efficient lighting – for example magnetic fluorescent ballasts (Koomey, Sanstad, & Shown, 1996) and CFL (Menanteau & Lefebvre, 2000) – have provided evidence of the slow diffusion of new energy-efficient lighting technologies. In an engineering-economic analysis, Koomey et al. (1996) found that efficient magnetic fluorescent ballasts represented a good investment for 99% of the commercial building stock, and a moderately good investment for 0.7% of the commercial building stock.[21] This efficient magnetic fluorescent ballast technology was first developed and introduced on the market in the 1980s, but this technology faced very slow adoption rates; only commensurate with

[21] In their analysis, Koomey et al. (1996) defined a good investment as an internal rate of return (IRR) of 20% real and higher, and a moderately good investment as an IRR of between 6 and 20% real.

the rate at which states implemented efficiency-technology standards. They argue that this evidence for the under-adoption of the more efficient ballasts proves there is an economic inefficiency in the market for energy-efficiency. Koomey et al. (1996) conclude that market mechanisms are not adequate for promoting cost-effective improvements in energy-efficiency, and that there are benefits in establishing minimum efficiency regulations to counteract this failure.

5.4 Policy Intervention

Market failures and barriers which prevent socially optimal levels of investment in energy efficiency are the primary reason to consider government intervention. Brown (2001) cites that in many case, public policies can be implemented to eliminate or compensate for market imperfections, hence enabling the markets to function in a more socially optimal manner. But in other instances, policies might not be able to eliminate the failure or the costs to do so might outweigh the benefits to be gained.

There are a number of policies in a policymaker's toolbox for promoting greater levels of energy efficiency. Early efforts to reduce energy-use in all sectors of the U.S. economy were initiated in the 1970s in response to concerns over U.S. energy security (OTA, 1992). Federal programs designed to promote energy-efficiency in buildings have included financial incentives (tax credits, loan guarantees, weatherization grants); Federal leadership providing public recognition for voluntary energy savings; research, development and demonstrations; codes and standards; and information provision (technical assistance, appliance labels and energy audits) (OTA, 1992).

Programs at the state and utility level have also promoted greater energy-efficiency. Utility demand-side management (DSM) programs and integrated resource planning (IRP) programs have been used by utilities and states under the recognition that enhanced consumer building efficiency can be a financially attractive option to building new power plants. Furthermore, these programs are supported by policy makers who see untapped economic and energy potential for speeding up the adoption of energy-efficient technologies in all sectors (OTA, 1993).[22]

In later years, utility DSM programs entered into a new era in which the focus is on so-called market transformations. Market transformations are a process by which energy-efficient technologies are introduced into the market and over time, capture a large portion of the eligible market leaving lasting changes in the level of energy-efficiency (Nadel & Geller, 1996). Market transformations seek to apply lasting changes to the market through the cooperative efforts of many organizations and by attempting to identify and address the barriers that inhibit widespread energy-efficiency.[23]

The U.S. government at both the state and national level has been active in promoting energy-efficient lighting. Programs and policies have included providing objective information on technical options and cost-effectiveness; R&D on lamps, fixtures, design tools and human factors of lighting; product rating and labeling; supporting electric utility programs and planning; government procurements of energy-efficient lighting technologies; legislated mandatory efficiency standards; and voluntary programs and incentives (Mills, 1995). Several of these

[22] For an overview on DMS and IRP programs see (OTA, 1993).
[23] For a review of market transformation programs see (Geller & Nadel, 1994).

types of programs have been chosen to be tested in this analysis. These chosen policies have been integrated into five policy scenarios, which will be described in the next chapter.

CHAPTER III. METHODOLOGY

The methodological approach used in this analysis is a simulation model of technology diffusion. A solid-state lighting commercial market penetration (SSL CMP) model is constructed in STELLA, a dynamic simulation software tool.[24] The SSL CMP model simulates SSL diffusion through the U.S. commercial building sector over a twenty year time period. This model provides a unique approach to modeling the epidemic behavior of technology diffusion and different policy options, and exploring the CO_2 emission reductions and energy savings from a lighting market transformation to SSL. The advantages of this model include:

- Building the SSL CMP model using the STELLA simulation modeling software facilitates a systems approach to modeling the process of technology diffusion;

- The SSL CMP model is a richer model for simulating the process by which an innovation is diffused through the market because epidemic-type dynamics can be included; and

- Using the SSL CMP model to explore policy instruments will create a better understanding of how these instruments can affect the diffusion process.

This chapter will begin with a brief introduction to energy-economic modeling, including a summary of simulation modeling and an example of an energy-economic model currently used

[24] The STELLA software is available from: www.iseesystems.com.

in U.S. energy policymaking. Next, an overview of the methodology of building the SSL CMP model is provided along with assumptions made in building this model. Finally, the six scenarios that are tested using the SSL MP model are summarized.

1. Introduction to Modeling

"All models are wrong, but some are useful" -George Box

A model can be thought of as representation of some part of the real world, usually in a different medium – and with differences in scale or simplification. A simulation model attempts to mirror the interrelationships and processes of a real-world system; hence the changes that occur in a model are said to *simulate* the changes that would occur in the real word system. How closely the model is able to mirror the real world system though, is heavily dependent on the assumptions used and the structure of the model. Models are particularly important analytical tools for policy analysts, who must often make policy recommendations in the face of complex interactions that surround an issue (Stokey & Zeckhauser, 1978).

The Department of Energy (DOE) uses the National Energy Modeling System (NEMS), a computer-based energy-economic model, to generate forecasts of energy demand, supply, imports and forecasts for the mid-term (20 to 25 years out in time).[25] This model is also used to project the economic, energy and environmental impacts from alternative energy policies or other influences. It is important to understand that the forecasts created using the NEMS model (and by any other model for that matter) should not be interpreted as a statement of what will

[25] For an overview of the structure and methodology used in the NEMS model see (EIA, 2003b).

happen in the future; rather they should be used as a guideline to what could happen, given the assumptions and methodology used to create the model (EIA, 2003b). The NEMS model (with minor variations) was recently used to explore the potential of public policies to foster clean energy technology solutions to the nation's energy and environmental problems. This study was an interagency report entitled "Scenarios for a Clean Energy Future" commissioned by the DOE Office of Energy-Efficiency and Renewable Energy (Interlaboratory Working Group, 2000).[26]

In this thesis, modeling with STELLA provides a unique advantage in that it allows the user to gain a better understanding of the dynamics of a complex system. The model simulation allows for a clear accounting of feedback, dynamics, and consequences from policy decisions.

2. Model Construction

Building a model using the STELLA simulation modeling software allows the technology diffusion of SSL to be studied using a systems approach. The SSL CMP model has been built to simulate the process of the technology diffusion of SSL in the U.S. commercial building sector. The commercial building sector was chosen because of its significance as an end-consumer of energy for lighting; in 2001 the commercial building accounted for 51% of primary energy required for lighting, while the residential sector followed with 27%, and the industrial and stationary outdoor sectors 14% and 8%, respectively (DOE, 2002).

[26] The interagency group was comprised of scientists from Argonne National Laboratory, Lawrence Berkeley National Laboratory, the National Renewable Energy Laboratory, Oak Ridge National Laboratory, and Pacific Northwest National Laboratory. This report analyzed portfolios of approximately 50 policies, in three different scenarios: a business as usual scenario, a moderate scenario, and an advanced scenario. Critical policies for the building sector in particular included efficiency standards for equipment, and voluntary labeling and deployment programs.

In the SSL CMP model, commercial building lighting demand is projected from 2005 until 2025. In the year 2005, a portfolio of different conventional lighting (CL) technologies meet this demand, and there is no SSL in use. The model simulates the market penetration of SSL to estimate how SSL will displace CL in the twenty year time period under study. The "engine" of technology choice is simple payback; defined as when the characteristics of SSL (*e.g.*, lifetime, cost, and efficacy) become such that the higher initial investment of SSL can be recouped in a certain number of years time, then a certain percentage of the lighting market purchases that month will go to SSL. The structure of the SSL CMP model is partially based on the modeling approach used in previous DOE SSL modeling reports (DOE, 2001, 2003b). (An overview of the DOE (2003b) model was given in Chapter II.) The SSL CMP model differs from this DOE model in a number of different ways, and these distinctions will be highlighted throughout the next section of this chapter. One of the prominent differences is the scope of the models. While the DOE models estimated SSL market penetration in four sectors (commercial, residential and industrial buildings, and outdoor stationary) of the U.S. economy, the model used in this thesis encompasses only the commercial building sector. Furthermore, the SSL CMP model integrates the epidemic effect of technology diffusion into the model, whereas this effect was not accounted for in the DOE models.

The model can be broken down into three primary components:

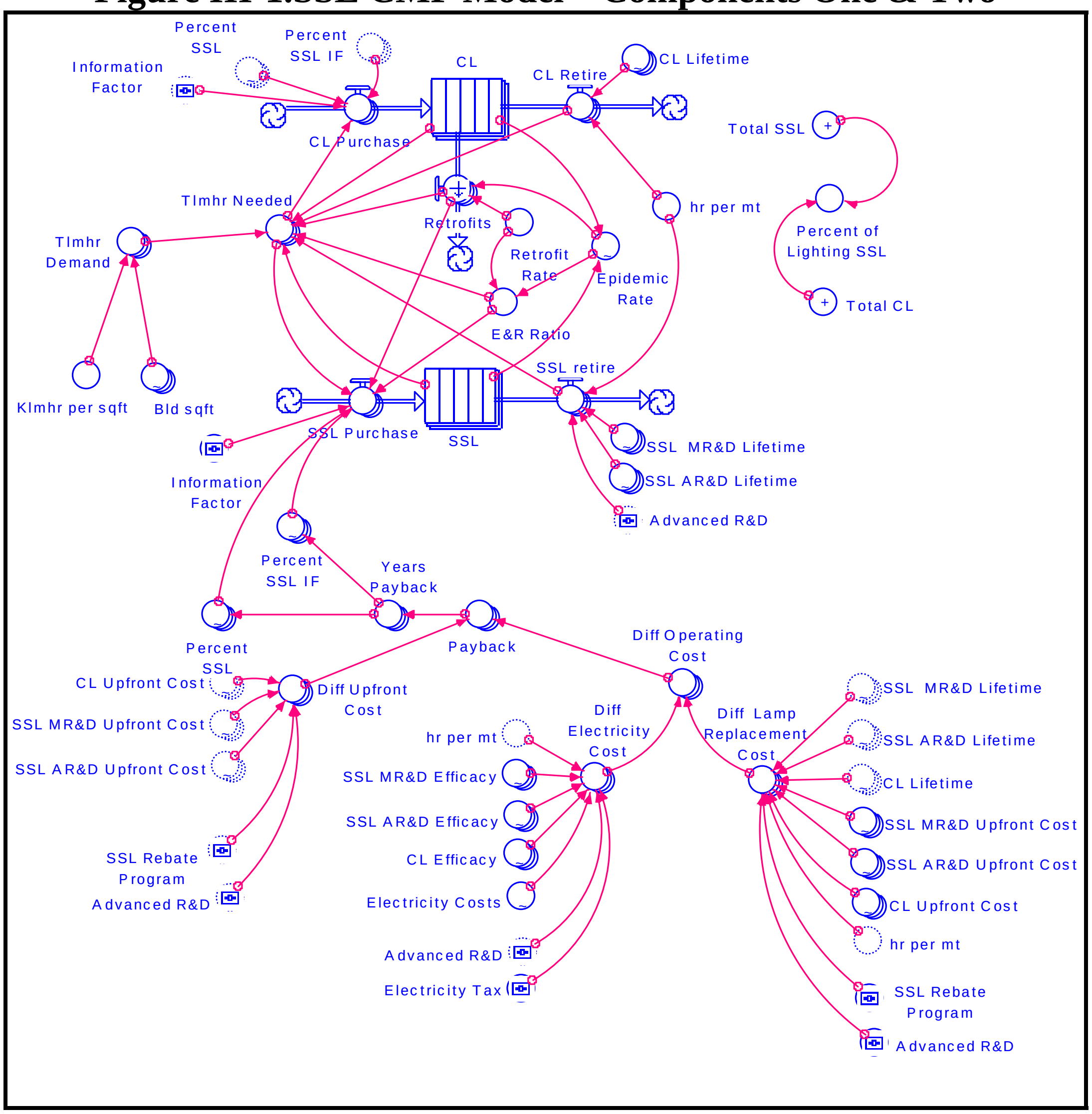
(1) Lighting Stocks & Lumen Demand;

(2) Payback Calculation; and

(3) Carbon Dioxide Emissions & Energy Consumption.

Each of the three components is described below. Further detail on the structure of the SSL CMP model has been incorporated into a table with all model elements, their units, and an abbreviated description of each element; this table has been included as Appendix D. For full transparency of the SSL CMP model, the STELLA modeling code is found in Appendix F. In Figure III-1, a diagram of the first and second components of the SSL CMP model is shown.

Figure III-1.SSL CMP Model – Components One & Two



2.1 Component One – Lighting Demand & Lighting Stocks

The first major component of the SSL CMP model (located in the top half of Figure III-1) handles lighting demand and the lighting stocks. First, the commercial sector demand for lighting service, or lumen demand, is projected from 2005 to 2025.[27] This demand is found by multiplying the monthly lighting intensity by the total commercial building floor space. The lighting demand grows 1.5% annually, directly corresponding to the rate at which the commercial building floor space is projected to grow (EIA, 2004a). It is assumed that the annual lighting intensity of 307 kilolumen-hour per square foot (klm-hr/sq-ft) for the commercial building sector (taken from the DOE (2003b) analysis) remains constant throughout the analysis.

Projecting Lighting Demand through 2020

According to the DOE (2002), commercial building lighting demand in 2001 was met by a number of different CL technologies from all three primary lighting technology groups: incandescent, fluorescent and HID. In the SSL CMP model, it has been assumed that the same distribution of lighting technologies used in the commercial building sector in 2001 is also present in 2005 – the first year accounted for in the model. This assumption does not take into account the dynamic nature of the market (*e.g.*, some technologies have likely gained market share in the commercial sector, while others have been retired and have lost market share) in this four year time span. Nevertheless, DOE (2002) contains the most recent national lighting data available; it is believed that this is the best available data for this analysis. In 2005, lighting demand is entirely met by CL and there is no installed SSL.

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[27] For modeling convenience, the SSL CMP model is broken down by monthly time periods rather than years; hence the model runs through 252 months.

Lighting Stocks

In the SSL CMP model there are two stocks – a SSL stock and a CL stock – that fulfill the commercial building sector lighting demand. The SSL and CL stocks are quantified in terms of the hours of lighting service they provide each month, and when added together must fulfill the total required lighting service for that month. For instance, if a total of 150 Teralumen-hours (Tlm-hr) of lighting service is required in one month, then the CL stock might contain 125 Tlm-hr and the SSL would then contain 25 Tlm-hr.

Disaggregating the Lighting Market by CRI

In the actual marketplace, lighting technologies are selected by consumers based on a number of criteria. Such criteria include: efficacy, lifetime, quality of light, aesthetic appeal of lamp design, and convenience of purchasing and maintenance. To realistically model the purchasing decisions made in the lighting market, one needs to take into account how lighting technologies compete against one another. Different types of visual tasks require certain qualities of light. One metric that captures fundamental differences between the qualities of light emitted from different lighting technologies is the color-rendering index (CRI). The CRI is a measure of how surface colors appear when illuminated by the lamp, compared to how they appear when illuminated by a reference source of the same temperature. (See Chapter II for a description of CRI.)

In the SSL CMP model, lighting in the commercial building sector has been broken down into four groups, or bins, based on the quality of light that is required. These four bins are named: very high CRI; high CRI, medium CRI and low CRI. This approach to modeling the lighting market using CRI bins was also used in the DOE (2003b) SSL model. Table III-1 explains the breakdown of these four CRI bins by their CRI values, and the specific lighting technologies that fall into each bin in the commercial building sector.

Table III-1. Conventional Lighting Technologies by CRI Bin

CRI Bin	CRI Values[1]	Commercial Lighting Technologies [2]
Very High CRI	100-91	**Incandescent:** Standard general service & reflector, Halogen Quartz, Halogen-reflector low voltage, low wattage
High CRI	90-76	**Fluorescent:** T8 <4feet, T8-4feet , T8 U-bent, T12 >4feet, Compact plug-in, Compact screw base
Medium CRI	75-41	**Fluorescent:** T12 <4feet, T12 -4feet, T12- U-bent, Circline **HID:** Metal halide
Low CRI	40-0	**HID:** Mercury vapor, High pressure sodium, Low pressure sodium

[1]CRI bin breakdown based on (DOE, 2003b).
[2] Lighting technologies placed in CRI bins based on CRI value given in (DOE, 2003b) Table 2-1.

In the SSL CMP model there are four SSL bins and four CL bins, for a total of eight bins. Solid-state lighting and CL only compete against one another on a bin-to-bin basis. For instance, VH CRI SSL can only compete against VH CRI CL. One of the major assumptions made in this thesis, as well as in (DOE, 2003b), is that lighting demand in each CRI bin will remain in that CRI bin between 2005 and 2025. Hence, if VH CRI lighting is required today for a certain purpose or task, only VH CRI lighting technologies will be able to supply that need in 2025. There are some general problems with breaking down the lighting market by CRI, particularly for SSL (see Chapter II, Section 2 for a discussion of the problems with using CRI for SSL). In spite of this, it is believed that CRI is currently the best metric of lighting to provide the desegregation necessary for this model.

Characteristics of SSL & CL

Each of these eight bins (four SSL and four CL bins), has a unique set of performance characteristics (efficacy and lifetime) and cost characteristics, which change exogenously over time in the SSL CMP model. Forecasts have been gathered from DOE (2003b) as to potential performance improvements and cost reductions of SSL and CL technologies and these are described below.

Currently many different CL technologies supply lighting service in the commercial building sector. Due to time and resource constraints, each of these technologies could not be modeled independently in this thesis. Therefore, a weighted-average for the efficacy, lifetime and cost were created for each CRI bin, based on DOE lighting data. To accomplish this, all of the CL technologies are placed into one of the four CRI bins based on its CRI value. Average characteristics (performance and cost) for CL technology were found using data found in (DOE, 2002, 2003b). A weighted-average (weighted based on the distribution of lumens supplied in 2001, by lighting technology) is taken to determine aggregate characteristics for each of the four CRI bins.[28] The four CRI bins and their mean cost and performance characteristics are displayed in Table III-2. In the SSL CMP model these values represent CL technologies in 2005, and provide the baseline from which future improvements in the technology are projected. The CL costs are expressed in constant 2005 dollars. A detailed table of all CL technologies and their characteristics incorporated into the weighted-averages is included in Appendix B.

[28] The distribution of annual lamp output by lamp type (measured in Tlm-hr per year) for the commercial sector is found in (DOE, 2002) Table 5-8.

Table III-2. Average Characteristics of CL Technology in 2005				
CRI Lighting Type	**Wattage (W)**	**Efficacy (lm/W)**	**Lamp Life (khr)**	**Cost ($/klm)**
Very High CRI	105.5	15.2	2.6	1.01
High CRI	55.0	80.4	16.0	0.67
Medium CRI	129.5	71.6	18.3	0.15
Low CRI	278.2	85.5	19.9	0.93

According to the DOE (2003b), CL technologies are relatively mature and therefore have limited potential for improvement. But at the same time, these technologies are not standing still; to account for this, the medium improvement scenario established by DOE (2003b) for CL technologies has been incorporated into the SSL CMP model.[29] Table III-3 shows these relatively modest performance improvements and cost reductions that are assumed to take place linearly between 2005 and 2025. These improvements are applied to the 2005 cost and performance characteristics of CL which are shown in Table III-2.

Table III-3. CL Technology Improvements between 2005-2025				
	Very High CRI	High CRI	Medium CRI	Low CRI
Efficacy	5%	10%	10%	20%
Lifetime	10%	10%	10%	20%
Cost	-10%	-10%	-10%	-10%

Source:(DOE, 2003b)

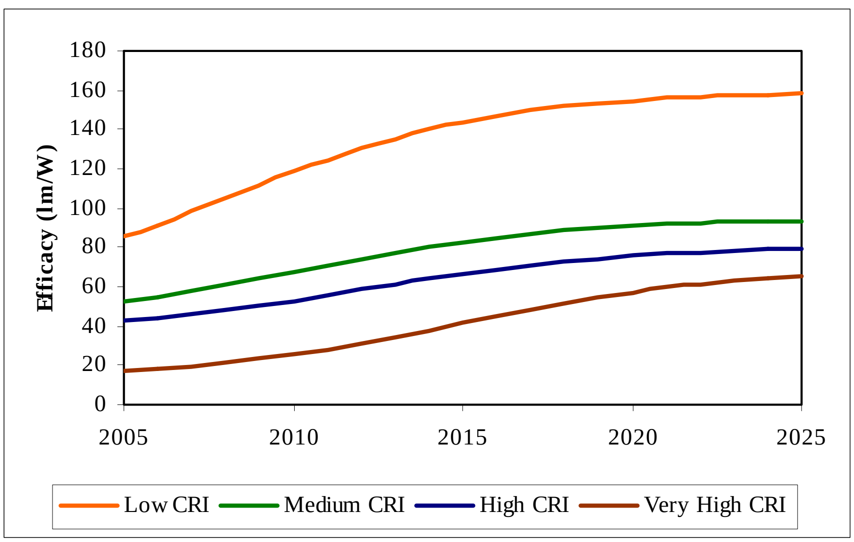
The improvements of SSL in terms of performance (efficacy and lifetime) and cost, are based on the DOE (2003b) technology improvement projections. These improvements were established assuming that there was a national annual investment in SSL of $50 million over ten years, funded by government and private industry. The SSL industry expects the performance characteristics and cost to follow a widely-recognized s-shaped trend of technology improvement

[29] DOE (2003b) established possible CL improvement scenarios: a low, medium and high improvement scenario. In the SSL CMP model only the medium improvement scenario was incorporated into the model. Furthermore, these improvements were projected for incandescent, fluorescent and HID lighting technologies; for this analysis the improvements were needed by CRI bin. Therefore, incandescent improvements were applied to VH CRI, fluorescent improvements were applied to both H CRI and M CRI, and HID improvements were applied to L CRI.

(DOE, 2003b). This trend is characterized by an s-shaped curve where at first a technology improves exponentially, then linearly, and finally asymptotically. In Figures III-2, 3, and 4, these performance improvements (efficacy and lifetime) and cost reduction are depicted. These technology improvements are broken down by bin; in general, the higher the CRI bin the lower the final target is for performance improvements. This reflects the trade-off that exists between color quality and performance. Furthermore, research on higher CRI SSL began more recently and in earlier stages than research on low CRI SSL, and creating higher CRI SSL entails greater technical complexity and more hurdles (DOE, 2003b).

The technology improvement curves used in this analysis were generated by the DOE (2003b), in which a major simplifying assumption was made that combined the characteristics of OLEDs and LEDs.[30] Hence, the following SSL curves encompass *both* LED and OLED SSL.

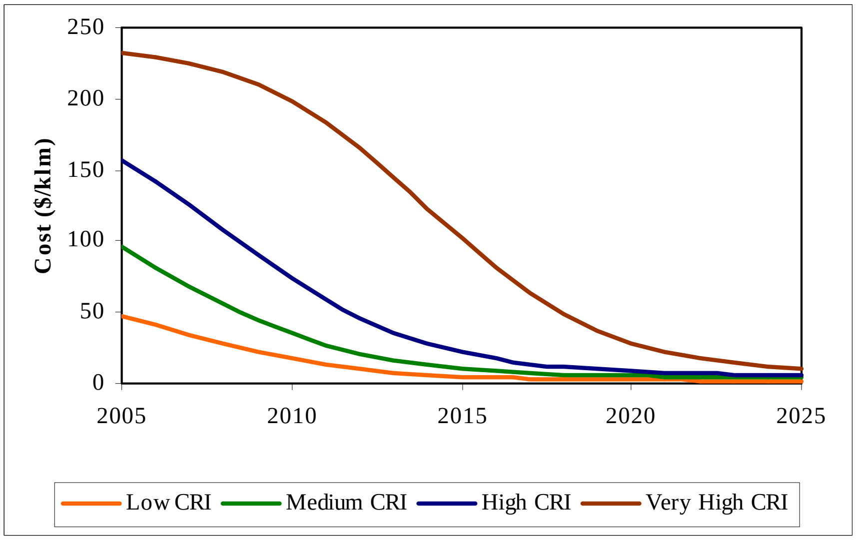
Figure III-2. SSL Efficacy Improvements by CRI Bin



Source: (DOE, 2003b)

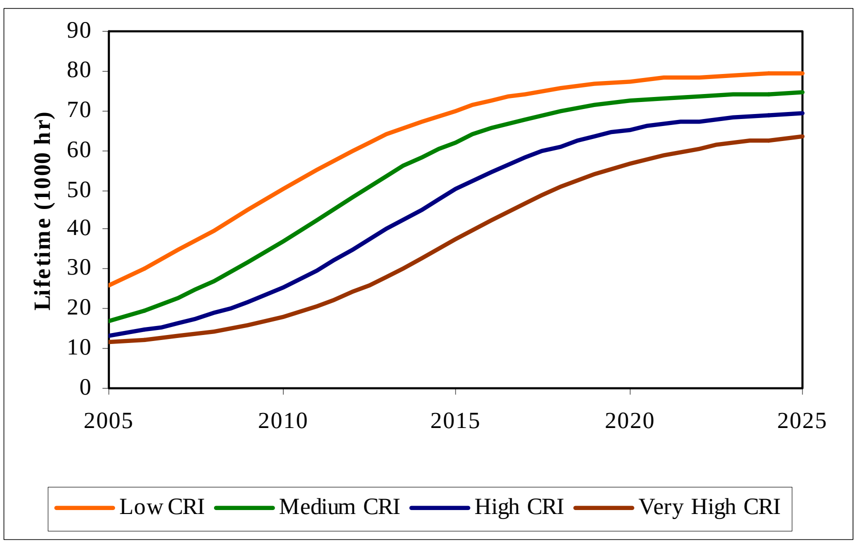
[30] For a discussion of the trade-offs that accompany this simplifying assumption, see(DOE, 2003b).

Figure III-3. SSL Cost Reductions by CRI Bin



Source: (DOE, 2003b)

Figure III-4. SSL Lifetime Improvements by CRI Bin



Source: (DOE, 2003b)

Forecasting the improvements of a new technology, particularly out twenty years in time is inherently fraught with uncertainly. Nevertheless, to estimate how a new technology will penetrate the market requires educated estimates on future performance and cost be formulated.

The performance improvements and cost reductions used in this analysis are directly from DOE (2003b). This DOE analysis in turn relied upon the performance and cost targets established in the SSL industry roadmaps ("The Promise of Solid State Lighting for General Illumination: Light Emitting Diodes (LEDs) and Organic Light Emitting Diodes (OLEDs)," 2001; Tsao, 2002); these roadmap targets are mainly used as guides represents the final target the s-curve asymptotically approaches in the DOE model. The slope and shape of the s-curves were estimated by DOE (2003b) based on consultation with experts in the SSL community, analysis of SSL research to date and on the performance and cost trends of similar technologies. Finally, it is important to recognize that these technology s-curves were built largely based on the SSL industry roadmaps that assumed a significant national investment into SSL was forthcoming; to date, this significant investment has not materialized (although some level of SSL R&D is ongoing). Hence, under a different investment scenario these performance trends might not be attained (Tsao, 2004).

Lighting Purchases

The two lighting stocks correspond to the installed base of SSL and CL technologies that provide lighting service. At the outset, all of the lighting demand is supplied by lighting in the CL stock; the SSL stock is set at zero.[31] As the model runs from 2005 until 2025, some of this lighting in the CL stock is displaced as SSL penetrates the market. The model calculates new purchases made on a monthly basis. In the model, new lighting purchases can be made via three different routes: new building construction; retired lighting, and lighting retrofits.

[31] In 2004 the use SSL in commercial buildings is limited, and hence for the purposes of this thesis assumed to be zero.

New Building Construction. The rate at which lighting is needed for new building construction depends on the rate of growth of commercial building floor space.

Retired Lighting. The retired lighting includes lighting technologies that reach the end of their useful lifespan and must be replaced. The stocks of lighting are retired at a rate that depends on the lifetime of the technology and the number of hours they are used per month.

Retrofit Lighting. The lighting retrofits from the commercial sector represent lighting that is retired before its useful life ends. In this model, the following two reasons for retrofits are accounted for:

(1) Some constant percent of retrofits occur every year, for example because of a building renovation. These retrofits occur at a relatively low constant rate; only 5% of an installed lighting stock is retrofitted each year according to (DOE, 2003b). In the SSL CMP model this annual retrofit rate is represented as a monthly retrofit rate of 0.042%.

(2) The second component of retrofits in this model is attributable to the epidemic effect. These epidemic retrofits are based on the assumption that as an increasing percentage of the installed stock of lighting shifts to SSL, the epidemic effect (see Chapter II, Section 4) will further enhance SSL diffusion. In this model, the epidemic rate is set to rise from zero to 0.04% per month, as the percentage of the

market that is captured by SSL goes from 0 to 100%. This relationship was estimated based on the assumption that if more SSL there was in use, more people would retire their CL early and switch to SSL. Zero was chosen as the lower limit of the epidemic rate because it was assumed that no epidemic effect would occur when no SSL was used. An upper limit of 0.04% per month was estimated under the assumption that the epidemic rate would not become greater than the 5% annual rate at which retrofits occur on a normal basis. This epidemic dynamic incorporated into the SSL CMP model represents an endogenous feedback loop, in that more technology adoption creates a feedback that generates further technology adoption.

The epidemic rate and the retrofit rate are combined, together providing the total rate of monthly retrofits. Of these retrofits, those attributed to the epidemic effect are automatically fed into the new SSL purchases that month. The rationale behind this is that if new retrofits are undertaken explicitly because consumers are persuaded to retire their stock early and adopt SSL, the model should reflect this in channeling the new lighting purchase directly to SSL. The remainder of the lighting retrofits (due to solely the retrofit rate) move into the large pool of new lighting needed in each month. From this pool, the payback "engine" (which is discussed in the following section) determines how much SSL and CL, respectively, are purchased.

The new lighting needed each month is equal to the total monthly lighting demand plus the amount of lighting that is retired or retrofit that month, and minus the installed stock of SSL and CL. Of the new lighting that is needed each month, this demand must be met by either purchasing SSL or purchasing CL. The SSL competes against CL in each of the four bins. For instance, VH CRI SSL only competes against VH CRI CL. The market share that is awarded to SSL each month is based on a payback calculation which will be described in the next section. The remainder of the purchases in that month goes to CL.

To represent the eight bins throughout the thesis, and for simplicity purposes, many of the converters, stocks and flows used in the SSL CMP model have been converted to one-dimensional arrays. Thus, the market penetration of SSL and the displacement of CL are tracked throughout the model based on their respective CRI bin. This feature has the additional benefit of allowing particular segments of the commercial building lighting market for SSL to be further analyzed, by tracking SSL diffusion in each CRI bin.

One important assumption made in both the DOE (2003b) report and in this analysis, is that SSL will be available that fits into existing light fixtures. As discussed in the previous chapter, there is still uncertainty as to whether SSL will compete with CL as a drop-in replacement "bulb," or whether it will usher in a new lighting paradigm that transforms the whole physical lighting infrastructure. In this latter scenario, one would expect SSL to diffuse into the general illumination market at a much slower rate because installing into existing buildings would involve higher switching costs (*e.g.*, fixture or wiring replacements).

An important distinction between the SSL CMP model and the analysis done by DOE (2003b) is that the SSL CMP model simplifies how lamp costs (measured in $/klm) are modeled. Lighting technologies can be purchased via the three routes outlined above, and in the SSL CMP model the SSL and CL only compete based on their lamp costs. Only taking into consideration lamp costs is a simplifying assumption, because in reality the lighting decisions in response to retrofits and new building construction would also take into account the cost of a fixture (and in some cases – ballasts) associated with each lighting technology option. Hence, in this analysis it is assumed that: (1) SSL will fit directly into existing CL fixtures and there will be no switching costs that might be associated with installing new fixtures or wiring; (2) The fixtures cost of SSL will be comparable to the fixture costs of CL and therefore can be omitted from being including in an investment calculation. The model can be modified to include these costs; such modification is reserved for future work.

2.2 Component Two – Payback Calculation

Investment decisions on energy-using technologies are typically framed in terms of a tradeoff between the upfront cost and operating cost (Decanio & Laitner, 1997). Simply payback is the decision "engine" in this thesis that determines the market share of SSL, and this calculation makes up the second major component of the SSL CMP model. The simply payback calculation is the ratio of difference in upfront costs of SSL and CL, to the difference in the operating costs between these technologies. This payback equation, also used in DOE (2003b) report, is expressed as:

$$(1) \qquad YearsPayback(yr) = \frac{-\Delta UpfrontCosts(\$/klm)}{\Delta EnergyCosts(\$/klm\cdot yr) + \Delta Lamp\,\mathrm{Re}\,placementCosts(\$/klm\cdot yr)}$$

The first variable in equation (1) represents the difference in the upfront costs, and is calculated in the SSL CMP model as,

$$(2) \qquad \Delta UpfrontCosts(\$/klm) = SSLUpfrontCost(\$/klm) - CLUnfrontCost(\$/klm)$$

where the SSL Upfront Cost and the CL Upfront Cost are exogenously determined variables that change over time. These upfront costs have units of dollars per kilolumen ($/klm), and as mentioned previously, only take into account the cost of the lamp (and not the fixture or ballast). The difference in operating costs is a sum of the difference in energy costs and the difference in lamp replacement costs. The calculation to determine the difference in annual energy costs is,

$$\text{(3)} \quad \Delta EnergyCosts(\$/klm \cdot yr) = HoursPerMonth(hr/mt) \cdot 12(mt/yr) \cdot ElectricityCost(\$/kWh) \cdot \left[1/SSLEfficacy(lm/W) - 1/ClEfficacy(lm/W)\right]$$

in which the electricity cost is an average cost per kilowatt-hour based on forecasts for the price of electricity use in the DOE (2003b) analysis, which in turn relied upon data from the EIA 2003 Annual Energy Outlook. Table III-4 shows the forecasted national average electricity cost for the commercial sector, following a conversion to constant 2005 dollars.[32]

Table III-4. Forecasted Electricity Costs

Year	Electricity Price ($/kWh)
2005	0.069
2010	0.067
2015	0.069
2020	0.072
2025	0.073

Source: (DOE, 2003b)

[32] It is important to note that the commercial electricity price is a nationwide average. In areas with higher than average electricity costs, the energy savings from more efficient lighting will be greater, and *visa versa.*

The number of hours per month lighting service is used has been set at 248 hours per month. This was calculated based on the average operating hour per day in the commercial sector of 9.9 hours (DOE, 2003b) Table ES-3, and an assumed 25 days of operation each month. The efficacies of SSL and CL are also factors that determine the total difference in the energy costs per month. Finally, the calculation is multiplied by 12 (the number of months in one year) to yield the difference in energy costs per year. The difference in the lamp replacement costs is calculated in a similar fashion:

$$\Delta Lamp\,\mathrm{Re}\ placementCosts(\$/klm\cdot yr) = HoursPerMonth(hr/mt)\cdot 12(mt/yr)\cdot \begin{bmatrix}(SSLUpfrontCost(\$/klm)/SSLLifetime(hr)) - \\ (CLUpfrontCost(K/klm)/SCLLifetime(hr))\end{bmatrix} \tag{4}$$

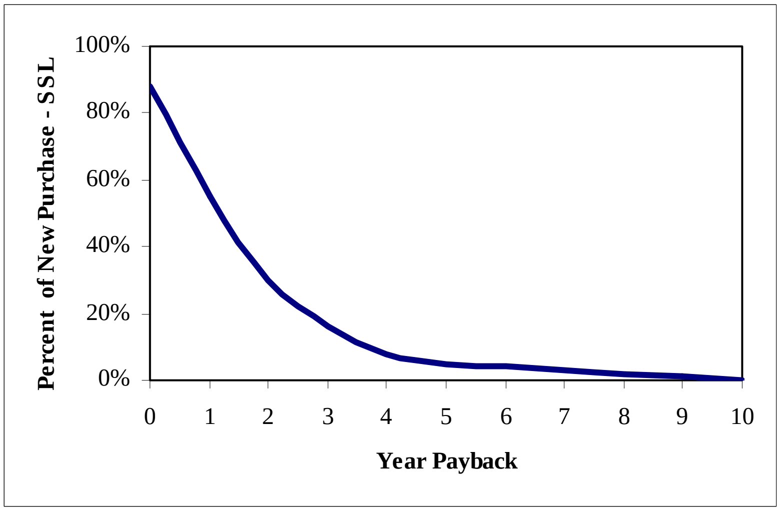
This lamp replacement cost is a function of the mean lifetimes of the lighting technologies, the number of hours they are used per month, and the upfront costs for each technology. In the DOE (2003b) model a labor charge was also included in this calculation, but has not been included in this analysis because the difference in installation times of SSL and CL is not known. Hence, the installation labor costs for SSL and CL technologies are assumed to be equivalent for the purposes of this analysis and are omitted from equation (4).

Finally, plugging in the difference in upfront costs, energy costs and lamp replacement costs from equations (2), (3) and (4), into equation (1) yields the payback (measured in years).[33] The length of this payback time period determines the percent of new lighting purchases that is awarded to SSL. The relationship between years payback and the percent of new lighting

[33] The units for each variable have been verified to provide a payback in years, and a detailed list of all model elements and their respective units is found in Appendix F.

purchases is depicted in Figure III-5. This graph was developed by Arthur D. Little, Inc. and is used in the DOE (2003b) analysis.[34] In this graph, as the number of years payback falls, SSL captures a greater percentage of new lighting purchases. For example, if the payback from investing in SSL is two years, then approximately 30% of new lighting purchases in that month go to SSL while the remaining 70% would go to CL.

Figure III-5. Years Payback & SSL Percent of New Purchases



Source: (DOE, 2003b)

This simple payback curve is based on empirical evidence that consumers use different discount rates when evaluating lighting purchases. Often consumers use high discount rates when evaluating energy technology purchases, which are well above market interest rates. Even though a payback of two years seems to be a sound investment choice, 70% of consumers who are making lighting purchases don't chose SSL. It could be inferred that these consumers are applying higher discount rates than those who represent the 30% purchasing SSL.

[34] DOE (2003b) cited that this curve was developed Arthur D. Little, Inc. However no study was cited and thus the methodology used to develop this curve is not known.

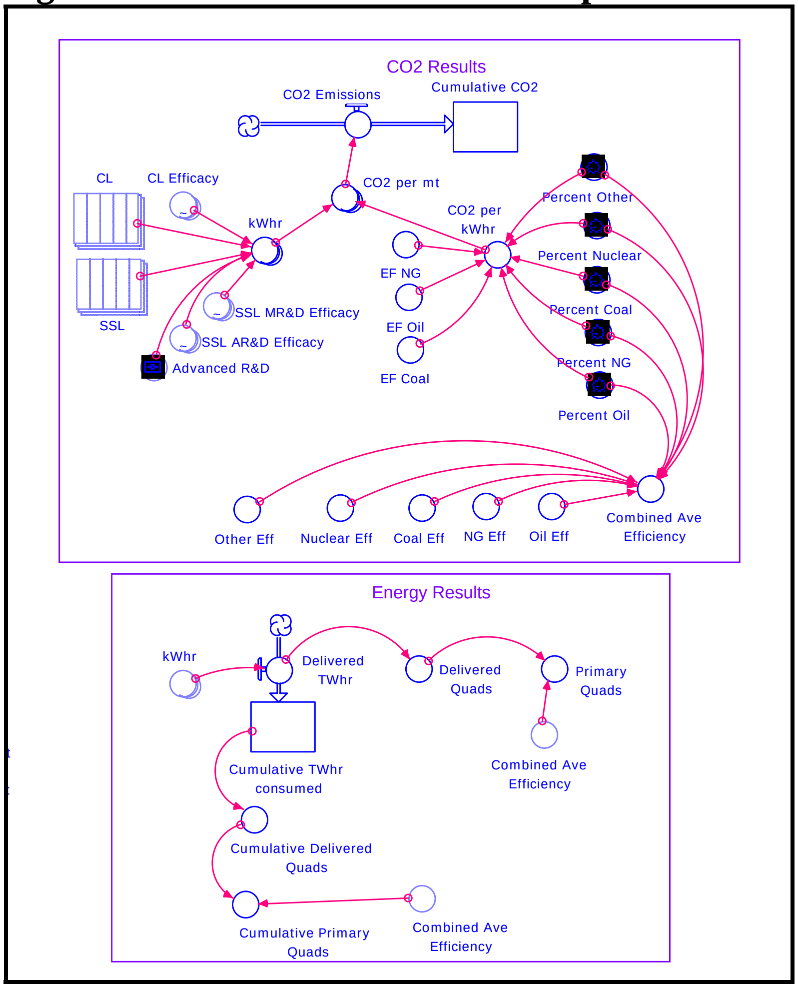
Simple payback is only one of several possible calculations that can be made to evaluate a lighting purchasing decision.[35] This evaluation method has both strengths and weaknesses. Simple payback is a relatively simple and intuitive method; the DOE (2003b) found it to be a robust indicator of purchasing behavior among consumers when they balance the trade-off between upfront costs and operating costs. However, an important limitation of the SSL CMP model is that by using simple payback as the "engine" of consumer purchasing decisions, the model has only a limited capability to simulate the complex behavior of consumers. Furthermore, simple payback does not incorporate any discounting which is usually performed when analyzing long-term investment decisions because of the time-value of money. Discounting the operating costs would lengthen the number of years payback, because the time value of money would reduce the savings over time. Therefore, the SSL CMP model underestimates the number of years payback and subsequently overestimates SSL market penetration.

2.3 Component Three – Carbon Dioxide Emissions & Energy Consumption

The final component of the SSL CMP model determines the total energy consumed by lighting between 2005 and 2025. The model incorporates CO_2 emission factors for different fuels to calculate the monthly CO_2 emissions from the lighting service supplied. This third component of the model is shown below in Figure III-6.

[35] An alternate, albeit more complicated method used to evaluate lighting purchases is life-cycle costing.

Figure III-6. SSL CMP Model: Component Three



The SSL CMP model calculates the energy (in kilowatt-hours) consumed at the end-user site, and then converts this to primary energy consumed by accounting for the electricity generation and distribution losses. Electricity generating efficiencies per fuel (see Table III-5), and an assumed 8% loss in electricity distribution were obtained from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation GREET model (Wang, 1998). The primary energy consumed is tracked by the SSL CMP model monthly, as well as cumulatively between 2005 and 2025.

The CO_2 emissions were calculated in the model using emissions factors for the portfolio of fuel sources that are used to generate electricity in the U.S. Emissions factors for CO_2 emissions released from electric utility plants were based on figures used in the GREET model (Wang, 1998).[36] Using a particular portfolio of fuels to generate electricity and their respective emission factors, a weighted-average CO_2 emission factor can be calculated by summing over *i* fuels,

$$EF_{Av} = \sum_i (EF_i) \cdot (\%_i) \tag{5}$$

The fuel mix used in the SSL CMP model along with the conversion factors and emission factors for different fuels are in Table III-5.

Table III-5. Default Portfolio of Energy Sources

	Oil	**NG**	**Coal**	**Nuclear**	**Other**	**Total/ Weighted Average**
Fuel Mix[1]	1.0%	14.9%	53.8%	18.0%	12.3%	100.0%
Generating Efficiency[2]	34.2%	39.4%	35.0%	34.0%	35.0%	35.5%
Emission Factor[3] (g/kWh)	896.6	562.9	1012.3	0	0	637.4

[1] (EIA, 2004b)
[2] (Wang, 1998)
[3] (Wang, 1998) Note that these emission factors are in grams per kWh consumed at the *end-use* site. An 8% transmission loss is incorporated into these emission factors.

These emission factors from Table III-5 are based on kilowatt-hours consumed at final end-user site, and incorporate an electricity transmission loss of 8%. The model incorporates two other possible sources of electricity: nuclear and "other" (*e.g.*, hydropower, solar, wind). Their CO_2 emission factors are both zero. The SSL CMP model is set up to allow the user to vary the portfolio of energy sources that generate the electricity. As a default, the model has been set up based on EIA data for fuels used to generate electricity in 2003. This default has been used to create the results discussed in the next chapter.

[36] The GREET model was developed by Argonne National Laboratory and sponsored by the U.S. DOE Office of Energy-Efficiency and Renewable Energy. The data used in this thesis was obtained from GREET version 1.4a.

Employing equation (5), the average CO_2 emission factor is about 640 g/kWh consumed at the end-use site, or 0.64 kg/kWh. The SSL CMP model uses this emission factor and calculates the total CO_2 emissions per month based on the lighting technologies (and their efficacy) that are fulfilling the lighting demand that month. The CO_2 emissions are tracked both monthly and cumulatively, between 2005 and 2025.

3. Scenario Building

Six scenarios were constructed in order to test the impact that specific policies could have upon the path of SSL diffusion, and subsequently, the CO_2 emission reductions achieved. Below, each scenario is described along with an account of how it is incorporated into the STELLA model. These scenarios were built and simulated in STELLA to gain a better sense of the impact that different policies could have on the SSL adoption. However, these simulations and their results (which are discussed in the following chapter) should not be interpreted as quantitative predictions. Furthermore, it is important to note that none of the scenarios have been subjected to any cost-benefit analysis, which would be an important later step in evaluating which policy option(s) yield the greatest net benefit to society.

These scenarios were chosen to represent a diverse selection of possible public policies that could foster the development and diffusion of SSL. However, these scenarios do not represent all of the possible policy options.[37] Policy levers such as government procurement or efficiency standards were not simulated in this thesis using the SSL CMP model. Furthermore there are many different scenario possibilities – for example, scenarios that incorporate different policy

[37] An exhaustive test of policy alternatives was outside the scope of this thesis. Several examples of policy options not tested in this thesis are government procurement and energy-efficiency (technology or building) standards.

combinations or that implement a policy for only a defined time period – which is an area for future research. Suggestions over future research will be further discussed in the concluding chapter of this thesis.

The six chosen scenarios are described in Table III-6.   The first three scenarios described below are also found into the DOE (2003b) report.

Table III-6. Six Scenarios Described		
Scenario	**Policy Lever(s)**	**Description**
1. Baseline Scenario	None	In this scenario, it is assumed that there is no further investment into SSL; hence SSL never penetrates the market for general illumination in the commercial sector. In this scenario, lighting demand is always fulfilled only by CL technologies. The number of years payback is artificially set to 15 in the model, to ensure that SSL never penetrates the market. (According to Figure III-5, SSL will only gain market share when its payback falls under 10 years.)
2.Medium R&D Investment	R&D Funding, Industry & Government Collaboration	In this scenario there is a national investment of $50 million dollars annually to develop SSL for general illumination. Due to government and industry cooperation in tackling critical technology problems, SSL performance (efficacy and lifetime) improves and costs are reduced. The s- curves for SSL were presented earlier in the model construction description. (See Figures III-2, 3, and 4.)
3. High R&D Investment	R&D Funding, Industry & Government Collaboration	In this scenario, a higher level of R&D investment is committed to SSL: $100 million dollars annually. As a result of more intensive research on SSL for general illumination, greater performance improvements and cost reductions are achieved than in the medium investment scenario. These higher performance improvements have been estimated by the DOE (2003b) in their analysis. These targets achieved with more intensive R&D are compared with the medium investment scenario targets in Table III-7 below.
4. Medium R&D Investment And Rebate	R&D Funding, Industry & Government Collaboration, Financial Incentive (Rebate)	In this scenario, the Medium R&D Investment is complemented by incorporating a rebate that reduces the upfront cost of SSL. This rebate reduces the upfront cost of SSL by 50 percent throughout the 20 year time period.
5. Medium R&D Investment and Tax on Electricity	R&D Funding, Industry & Government Collaboration, Tax	This scenario similarly combines the Medium R&D Investment with a second policy lever. Here, this lever is a tax of 15% which is applied to the cost of electricity for the commercial sector throughout the 20 year time period. Potential electricity demand impacts due to the electricity tax are not accounted for.
6. Medium R&D Investment and Information Program	R&D Funding, Industry & Government Collaboration, Information Program	This scenario also uses combines the Medium R&D Investment scenario with a second policy lever. In this scenario, an information program is established which provides consumers with more information about SSL. This program might be in the form of a demonstration and validation project, a voluntary labeling scheme (*e.g.* ENERGY STAR), or providing consumers with independent technical information so they can evaluate the pros and cons of SSL.

Table III-7 shows the SSL technology limits (which are depicted as the limits of the technology s-curves in 2025), which are used in the medium and accelerated R&D investment scenarios described above.

Table III-7. SSL Technology Improvement Limits				
	CRI Bin	**Efficacy (lm/W)**	**Lifetime (1000 h)**	**Cost ($/klm)**
Medium Investment Scenario	Low CRI	160	80	$ 2.00
	Medium CRI	95	75	$ 4.30
	High CRI	80	70	$ 6.00
	Very High CRI	65	65	$ 10.30
Accelerated Investment Scenario	Low CRI	225	100	$ 1.20
	Medium CRI	180	100	$ 2.50
	High CRI	160	100	$ 3.30
	Very High CRI	140	100	$ 5.80

Source: (DOE, 2003b)Note: Efficacy and lifetime values are rounded to the nearest 5.

The performance improvements and cost reductions used in this analysis are directly from DOE (2003b), which relied upon the performance and cost targets established in the SSL industry roadmaps ("The Promise of Solid State Lighting for General Illumination: Light Emitting Diodes (LEDs) and Organic Light Emitting Diodes (OLEDs)," 2001; Tsao, 2002). These roadmap targets are mainly used as guides as to the final improvement targets (Table III-7) that the SSL s-curves asymptotically approach in 2025.

The slope and shape of the s-curves were estimated in DOE (2003b) based on consultation with experts in the SSL community, analysis of SSL research to date and on the performance and cost trends of similar technologies. It is important to keep in mind that these SSL technology limits represent anticipated technology targets which may not be achievable by 2025 (DOE, 2003b). Or conversely, these SSL targets might be reached prior to 2025. The SSL industry is a global industry, and there are a number of other countries with national investment projects already underway for SSL.[38] Solid-state lighting technological development will be shaped not only by U.S. research, development, commercialization and public policy, but also by similar efforts in countries around the world. Thus, the technology targets and rate of technological development used in this analysis might also be conservative.

All five of the policy scenarios used in this thesis are based on either a medium or accelerated R&D investment into SSL. These two investments reflect different levels of public money that could be invested into research, development and deployment of SSL. Along with a government investment into SSL, the private sector will play the critical role in developing SSL as a suitable replacement for conventional lighting. A public-private partnership, such as Next Generation Lighting Initiative (S.1166) currently before Congress, could fulfill this purpose by creating a coordinated effort (funded annually for ten years at $50 million) between industry, academia, national laboratories and other supporting agencies, to develop and diffuse SSL technology.

[38] National R&D investments in SSL have been undertaken by countries such as China, Japan, Taiwan, and China.

CHAPTER IV. RESULTS

1. Chapter Overview

The SSL CMP model was run to simulate the six scenarios that are described at the end of Chapter III. The results from these simulations are described in this chapter. The energy and carbon dioxide (CO_2) impacts of each policy scenario are analyzed and compared to the Reference Scenario. Solid-state lighting market penetration by CRI bin are also analyzed under each scenario to better understand the effect that different policies have on different parts of the lighting market for commercial buildings. Integrating the epidemic effect was a unique feature of the SSL CMP model; hence, each scenario is tested to determine the impact that the epidemic rate had in each scenario. Finally, a sensitivity analysis is performed to assess how sensitive the final outcomes are to the high leverage assumptions made over certain policies responses.[39]

As a reminder, the six scenarios that have been considered in this thesis are:

- **Scenario 1 –** Reference Scenario
- **Scenario 2 –** Medium R&D Scenario
- **Scenario 3 –**Advanced R&D Scenario
- **Scenario 4 –**Medium R&D Scenario, Plus Electricity Tax
- **Scenario 5 –** Medium R&D Scenario, Plus Rebate
- **Scenario 6-** Medium R&D Scenario, Plus Information Program

[39] Because there are over 30 variables in this model, a sensitivity analysis was conducted on only those variables that were thought to be high leverage.

The references scenario represents the base case in which there is no SSL technology developed and conventional lighting (CL) technologies continue to fulfill lighting demand through 2025. In Scenarios 2 through 6, five different combinations of public policies are implemented to encourage and accelerate SSL diffusion. These policies scenarios are contrasted with both the reference scenario and with each other, to assess how different types of public policies can impact the diffusion of SSL within the parameters of the SSL CMP model.

2. Energy Impacts

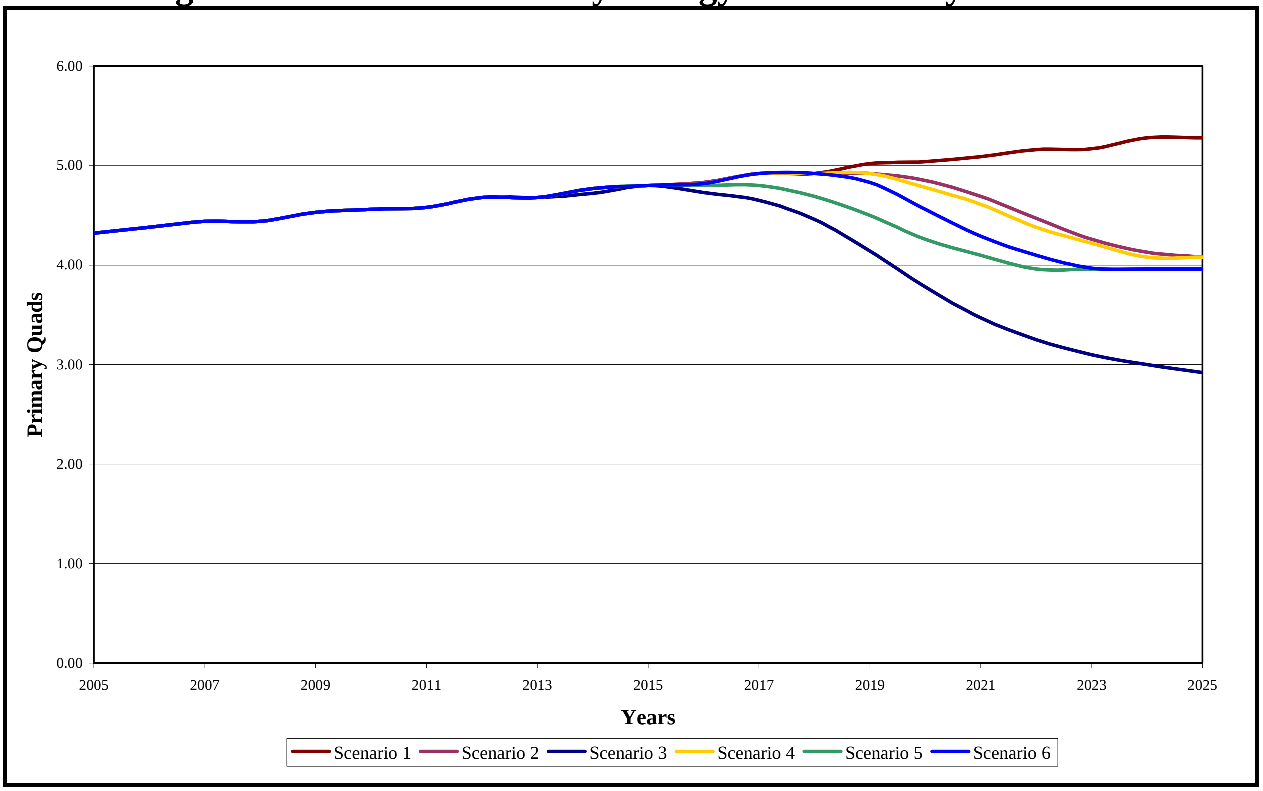
The results for primary energy consumption between 2005 and 2025 in each of the six scenarios are shown in Figure IV-1. The primary energy is measured in quads, and takes into account energy losses during electricity generation and transmission.[40] Commercial buildings in 2005 consume approximately 4.3 quads of primary energy for lighting. In Reference Scenario 1, primary energy consumption grows to 5.3 quads by 2025; in this scenario no SSL is deployed and the performance of CL improves only modestly. In Scenarios 2 through 6, SSL is developed and penetrates the commercial building market, which reduces the primary energy consumed by lighting in 2025, relative to the Reference Scenario.

Several things are immediately noticeable from the graph in Figure IV-1. First, in Scenarios 2 through 6 the reductions in primary energy consumption all resemble an inverse-s-shaped curve. This can be attributed to the s-shaped curve of SSL diffusion, which in turn is influenced by the s-curves that describe SSL technology improvements and the relationship between years payback and percent of new market purchases that are SSL. Second, primary energy savings from SSL

[40] See Chapter III for a description of how primary energy is calculated in Component III of the SSL CMP model.

aren't realized prior to 2015 in any of the scenarios. This implies that in the next ten years, SSL used for general illumination will likely have little to no impact on primary energy demand for lighting in commercial buildings. Primary energy savings accredited to the purchase and use of SSL begins to accrue only after 2015. Scenario 3 (Advanced R&D) provides the earliest energy reduction, beginning in 2016. Energy reductions begin in 2017 under Scenario 5 (Medium R&D plus Rebate), and later in 2019 under Scenarios 2, 4, and 6.

Figure IV-1. Annual Primary Energy Consumed by Scenario



By 2025, Scenario 2 provides the greatest energy reductions from the Reference Scenario; 2.4 quads of primary energy are saved in Scenario 2. This is 45% below the projected primary energy demand in the Reference Scenario. Primary energy reductions relative to Reference Scenario are quantified in Table IV-1. Scenarios 2, 4, 5, and 6 all provide annual energy savings between 23-25% by 2025 relative to the Reference Scenario; this translates into between 1.2 and 1.3 quads of primary energy.

By 2020, Scenario 3 already provides the greatest energy savings (25%) of the five scenarios relative to the Reference Scenario. Scenarios 5 and 6 follow, providing an energy savings of 15% and 10%, respectively in 2020. Under Scenarios 2 and 4, SSL is slower to provide significant energy savings; primary energy is only reduced by approximately 4-5% by 2020.

Table IV-1. Annual Primary Energy Consumption Reductions Relative to Reference Scenario 1

	Sc. 2		Sc. 3		Sc.4		Sc.5		Sc. 6	
	(Quads/yr)	(Percent)	(Quads/yr)	(Percent)	(Quads/yr)	(Percent)	(Quads/ur)	(Percent)	(Quads/yr)	(Percent)
2005	0	0	0	0	0	0	0	0	0	0
2010	0	0	0	0	0	0	0	0	0	0
2015	0	0	0	0	0	0	0	0	0	0
2020	0.2	4%	1.3	25%	0.3	5%	0.8	15%	0.5	10%
2025	1.2	23%	2.4	45%	1.2	23%	1.3	25%	1.3	25%

Scenario 3 (Accelerated R&D) generates the most significant overall energy impact of the five SSL policy scenarios considered in this thesis. This scenario produces a 45% reduction in primary energy consumption from the Reference Scenario by 2025. Furthermore, energy savings under Scenario 3 begin to accrue the earliest among the scenarios considered. Comparatively, Scenario 2 (Medium R&D) only generates a 23% reduction in primary energy consumption by 2025 and because the energy savings begins to occur later – less energy is saved on a cumulative basis. (Cumulative reductions in CO_2 are discussed in the next section of this chapter.)

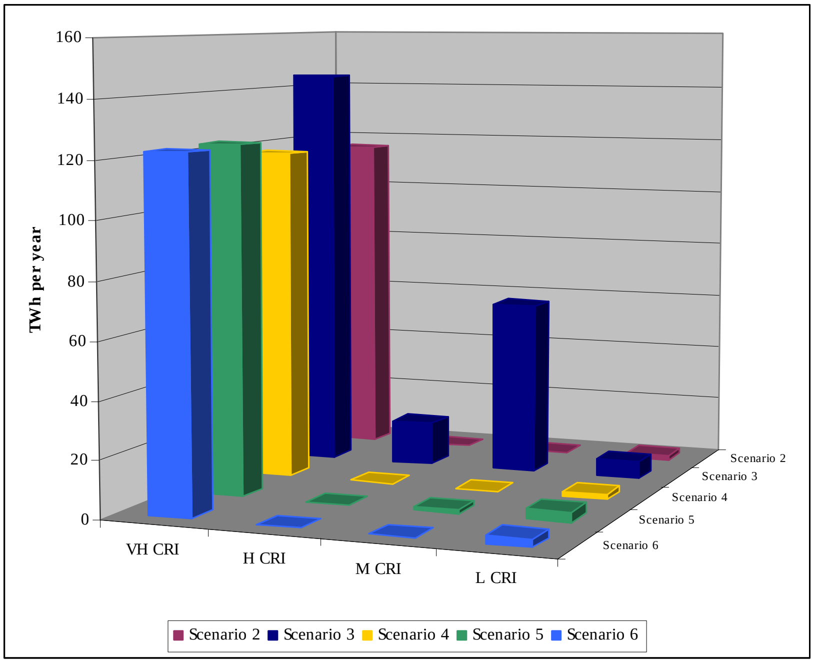
Scenarios 4 – 6 were designed to supplement a medium R&D investment with an additional policy mechanism. A tax incentive, rebate and an information program were integrated into the model, and according to the primary energy results in Figure IV-1 and Table IV-1, the rebate (Scenario 5) is the most effective policy of the three policies. In addition to providing a 25% reduction in primary energy in 2025, the rebate is able to generate the earliest (2017) primary energy savings of these three scenarios. The information program (Scenario 6) also generates a 25% reduction in primary energy in 2025, but the energy savings aren't seen until approximately 2019. However, once market penetration occurs under the information program scenario, primary energy consumption is reduced at a steeper rate than with the rebate. Despite this, energy reduction impacts in Scenarios 5 and 6, the energy consumption ceases falling following 2023, and remains flat throughout 2025.

The rebate policy appears to be more influential initial SSL deployment and generating energy savings *early* in the diffusion process. The information program accelerates the rate at which primary energy consumption falls. The electricity tax provides only a small improvement from Scenario 2 (Medium R&D); its energy reduction path is only slightly discernable from that of Scenario 2. The electricity tax provides a small early advantage by reducing energy consumption from 4 to 5% in 2020. However overall, the tax does not have a significant impact above and beyond the medium R&D investment.

By 2025, the annual energy savings from in Scenarios 2 through 6 are shown in Figure IV-2. These savings are broken down by CRI bin, and represent SSL energy savings relative to

Reference Scenario 1. Energy savings are presented in annual Terawatt-hours (TWh) – this unit represents the energy consumed at the user end-site.[41]

Figure IV-2. Annual Energy Savings per CRI Bin in 2025



In Scenarios 2, 4, 5, and 6, the vast majority (96-98%) of the energy savings result from replacing VH CRI conventional lighting. The VH CRI bin is predominately incandescent lighting. In these scenarios, SSL penetrating the L CRI bins generates relatively smaller energy savings (1-3% of total savings). In Table IV-2 the results of Scenario 2 and Scenarios 4 through 6 are given. Scenario 2 (Medium R&D) in particular, generates an energy savings of 117.3 TWhr which are highly concentrated (99%) in the VH CRI bin. In the bottom half of Table IV-2, the incremental energy savings in addition to Scenario 2 are shown for Scenarios 4 through 6. In these three scenarios, additional policy levers are implemented to accelerate the diffusion of

[41] The conversion from energy consumed at the user end-site (TWh) to primary energy (quads) consumed at the electricity generation site; is performed in the model by dividing the TWh by the account generation efficiencies and a transmission loss of 8%.

SSL. By implementing these policies, greater energy savings in realized by 2025. Overall, Scenario 5 (Medium R&D, Plus Rebate) generates the most additional energy savings by 2025 (10.5 TWh more than Scenario 2). Most of the additional energy savings accrue in the VH CRI bin, although some energy is also saved in the L CRI bin in Scenarios 4 through 6. Scenario 5 (Medium R&D, Plus Rebate) is successful in generating energy savings in the M CRI bin because it lowers the upfront price of SSL such that SSL can become competitive with CL technologies.

Table IV-2. Annual Energy Reductions for Select Scenarios in 2025
(in TWh/yr, Relative to Reference Scenario 1)

	VH CRI	H CRI	M CRI	L CRI	Total
Scenario 2	115.7	0	0	1.6	**117.3**
	Incremental Energy Reductions Relative to Scenario 2				
	VH CRI	**H CRI**	**M CRI**	**L CRI**	**Total**
Scenario 4	2.1	0.0	0.0	0.2	**2.3**
Scenario 5	7.3	-0.1	1.4	2.0	**10.5**
Scenario 6	7.0	0.0	0.0	1.1	**8.1**

Interestingly, in Scenario 5 the H CRI bin actually consumes 0.1 TWh *more* energy than in Scenario 2. This is because the SSL that penetrates this market is actually *less efficient* than the average efficiency of the CL technologies. The SSL is able to penetrate the market in the SSL CMP model because of the epidemic effect; hence, the use of SSL in the commercial sector in one bin has a spillover affect on other bins. A small amount of CL technology is retired early and less-efficient SSL is adopted because of these information spillovers. In reality, this could occur particularly because the unique features of SSL (*e.g.*, flexibility, longevity, durability, the ability to change the color of light, etc.) might persuade potential adaptors to choose SSL despite the fact that it is slightly less efficient than a comparative CL technology.

On the other hand, Scenario 3 (Advanced R&D) is able to generate significant energy savings in both the VH CRI and M CRI bins by 2025. In this scenario, 64% of energy savings accrue from the VH CRI bin while 27% of energy savings are from the M CRI bin. The H CRI bin represents 7% of energy savings and the L CRI generates 3%. The performance improvements and cost reductions that are realized through a higher R&D investment enable SSL to become competitive with CL in a number of different bins.

Later in this chapter, the SSL market penetration by CRI bin will be analyzed for each policy – this will allow for greater insight into how the market penetration of different lighting bins in the commercial building lighting sector compare with the energy savings per bin shown in Figure IV-2. Subsequently, more insight will be gained as to why certain policies generate the energy savings seen here.

How do these energy savings compare with earlier SSL market penetration reports? The DOE (2003b) SSL market penetration report found that under a medium investment scenario, 1.23 quads of primary energy would be saved on an annual basis by 2025. Under the accelerated investment scenario these energy savings rose to 3.51 quads. According to estimations based on Figure 8.1 in the DOE report, approximately 2.2 of these 3.51 quads can be attributed to the commercial sector (DOE, 2003b). (The remaining energy savings are due to the residential, industrial and outdoor stationary sectors.) The SSL CMP model energy savings reduction of 2.4 quads under the same accelerated investment scenario is comparable to the DOE result of approximately 2.2 quads. Unfortunately, commercial sector results were not specified for the medium R&D investment scenario in the DOE report, so no comparison between that estimate and this analysis can be made. However, the results of this analysis can be at least partially validated by comparing the energy reductions found using the SSL CMP model to the results from the DOE (2003b) analysis.

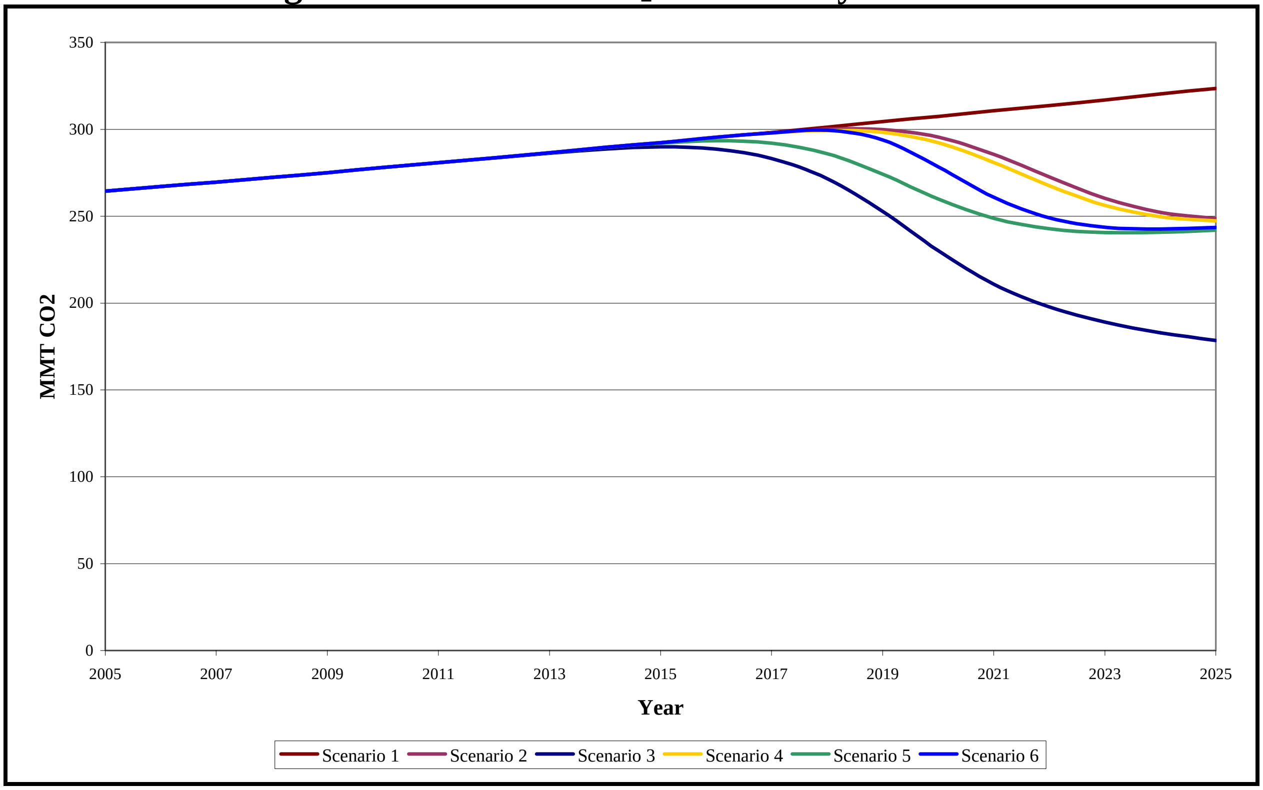
3. Carbon Dioxide Impacts

Carbon dioxide (CO_2) emissions are released when electricity is generated to power the lighting equipment used in the commercial building. In Figure IV-3, the annual CO_2 emissions released are graphed for each of the six scenarios that have been simulated in this thesis. This graph closely resembles that of Figure IV-1 because in all six model runs, model variables which affect the average CO_2 emission factor (mix of fuels used to generate electricity and the average efficiency of each fossil fuel generation process) were not changed.[42] This was done so that the all of the changes in CO_2 emissions could be attributed to the policies being tested in this thesis. Additional research could incorporate scenarios where the mix of fuels and their respective generation efficiencies change over time; however this work is reserved for future research.

Even though these features of the model are not varied in the current analysis, they are important features of the SSL CMP model because the model is run to the year 2025. By 2025 it is likely the fuel mix (and generation technologies) will be different than that of today, and hence this model allows that future analysis be capable of simulating different scenarios in which the fuel mix and generation efficiencies change over time.

[42] In addition to the mix of fuels and average efficiency of fossil-fuel combustion, other factors that might impact the primary energy consumption and CO_2 emissions relationship include: advanced clean power technologies such as coal sequestration or changes in the transmission losses over the electricity grid.

Figure IV-3. Annual CO_2 Emission by Scenario



Carbon dioxide emissions attributed to commercial buildings lighting consumption grow from 265 million metric tons of CO_2 (MMT CO_2) in 2005 to 324 MMT CO_2 in 2025; this represents a 22% growth in emissions over this 20-year time period.[43] To put this into perspective, the Energy Information Administration (EIA) of the DOE estimates that in 2002, the U.S. released a total of approximately 5,680 million metric tons of CO_2 from energy-related activities (EIA, 2003a). These energy-related CO_2 emissions were by far the most significant source (82.3%) of GHG emissions in the U.S. In the EIA Annual Energy Outlook 2004, energy-related CO_2 emissions are projected to grow 1.5% between 2002 and 2025, to reach approximately 8,074 MMT CO_2in 2025 (EIA, 2004a).[44] Hence, CO_2 emissions in 2025 of 324 MMT CO_2 due to

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[43] Based on a back-of-the-envelope performed in Chapter II, it was found that in 2002 the commercial building sector's lighting accounted for approximately 215 MMT CO_2. If one was to extrapolate back the 265 MMT CO_2 used here, emissions in 2002 would be slightly higher that this estimate.
[44] There are, of course a number of uncertainties with forecasting carbon emissions out to 2025.

commercial sector lighting would represent roughly 4.0% of total energy-related CO_2 emissions. In Table IV-3, the CO_2 emission reductions for the policy scenarios in the years 2015, 2020 and 2025 have been quantified.

Table IV-3. Annual CO_2 Emission Reductions **Relative to Reference Scenario 1 (MMT CO_2/yr)**			
	2015	**2020**	**2025**
Scenario 2	0.0	11.9	74.8
Scenario 3	2.4	77.2	145.0
Scenario 4	0.0	15.1	76.2
Scenario 5	0.2	47.5	81.5
Scenario 6	0.0	29.0	80.0

Figure IV-3 quantifies the reduction of CO_2 emissions in each scenario, relative to the Reference Scenario. The emission reduction trends are almost identically to the trends in primary energy consumption from Figure IV-1. In each of the five policy scenarios, CO_2 emissions are reduced below 2005 levels by 2025. These emission reductions begin in 2015 for Scenarios 2 and 5; and around 2019 for Scenarios 3, 4, and 6. The emission reductions achieved by Scenarios 2 and 5 in 2015 are relatively small, and no emissions reductions are gained by this time in the other scenarios. Hence; this implies that deploying SSL in commercial buildings is not a realistic policy mechanism for meeting potential shorter-term CO_2 emission targets that are established for the next ten years.[45]

Under Scenario 3 (Advanced R&D) there is a 45% reduction in annual CO_2 emissions in 2025. Under this scenario, by 2025 145 MMT of CO_2 are being prevented annually. There is a 23%

[45] This indicates that SSL in *general illumination* applications isn't likely to yield CO_2 emission reduction in this time frame; however there are some instances where LEDs are used in niche applications (*e.g.* the backlights of a liquid crystal display (LCD)) could provide energy-savings in the nearer term. For further information about these possibilities see (DOE, 2003a) and (Ton et al., 2003).

reduction of CO_2 emissions in Scenario 2 (Medium R&D) or 74.8 MMT CO_2. This figure rises only slightly to a 24-25% reduction by implementing additional policy mechanisms (an electricity tax, a rebate, or an information program). In absolute terms, additional reductions of between 1.5 and 6.5 MMT CO_2 can be achieved by implementing one of these policies. In addition to annual emissions, it is important to consider the impact that the different policy scenarios have on the cumulative CO_2 emissions released between 2005 and 2025. Cumulative emission reductions relative to the Reference Scenario are shown in Table IV-4.

Table IV-4. Cumulative CO_2 Emission Reduction Between 2005 & 2025 (Percent from Reference Scenario)

Scenario	Percent
2. Medium R&D	4.5%
3. Advanced R&D	13.0%
4. Medium R&D, Plus Electricity Tax	4.9%
5. Medium R&D, Plus Rebate	7.6%
6. Medium R&D, Plus Information Program	6.2%

The cumulative CO_2 emissions between 2005 and 2025 vary between scenarios because of the unique timing and rate of SSL market penetration for each scenario. Scenario 3 (Advanced R&D) again provides the most significant impact – a 13.0% cumulative reduction in CO_2 emissions when contrasted with the Reference Scenario. Scenario 2 (Medium R&D) provides a 4.5% reduction; when the electricity tax is added this savings rises to 4.9%. Scenario 6 (Medium R&D, Plus Information Program) generates a 6.2% reduction while Scenario 5 (Medium R&D, Plus Rebate) creates a 7.6% reduction in CO_2 emissions from the Reference Scenario. It is useful to compare the incremental effect of policies used in Scenarios 4 through 6, to Scenario 2 in order to gauge the impact of the electricity tax, rebate and information program. Of the policies considered in Scenarios 4-6, the rebate generates the biggest impact because it is successful in achieving earlier reductions in CO_2 emissions. However, some of the same observations made earlier for the energy reduction trends seen in Figure IV-1 also apply to Figure IV-4. For example, emission reductions in Scenarios 5 and 6 both level off around 2013. The emissions reduction trend occurs more rapidly under the information program, but is slower than the rebate to initiate emission reductions. Finally, Scenario 4 (Medium R&D, Plus Electricity Tax) creates only a minor reduction in emissions compared to Scenario 2.

Carbon dioxide emission trends under the policy scenarios considered in this thesis imply that 2015 is the earliest that SSL deployed to provide general illumination in the commercial building sector, will have an impact on CO_2 emissions. Therefore, given the assumptions made in the SSL CMP model, SSL in this particular sector of the market won't be able to contribute to meeting emission targets established for the next ten years (2005 until 2015). However, in the longer term, SSL has the potential to generate emission reductions. For instance, under Scenario 3, CO_2 emissions are 45% lower by 2025 than emissions in the Reference Scenario. This represents a reduction of 145 MMT CO_2 in 2025. This emission level is by far the greatest emission reduction achieved under the scenarios that have been tested in this thesis. Furthermore, in Scenario 2, emissions continue to fall through 2005, whereas in other scenarios the emission reductions stagnate around 2023. Emissions are able to continuing falling in Scenario 2 because the SSL more significant technical improvements and cost reductions allow SSL to penetrate all of the CRI bins where it can continually create energy savings through 2005.

In Scenario 2, CO_2 emissions are reduced by approximately 75 MMT CO_2 – slightly less than half the emission reductions that occur in Scenario 3. This result should not be construed as quantifying a precise relationship between amounts of funding devoted to R&D and the emission reductions possible. The emission reductions largely depend on SSL market penetration, which in determined in part by the economics of SSL (performance and cost). Future SSL performance improvements and cost reductions are difficult to predict out twenty years in time. In *general*, the assumption that a greater U.S. R&D investment in SSL will improve the performance and reduce the cost is relatively robust. Nevertheless there are a number of other factors that will factor into this relationship between 2005 and 2025 including: how effectively this money is spent, the nature of the government/industry partnership, the timing of important technical breakthroughs and incremental improvements, and foreign competition in the SSL industry.

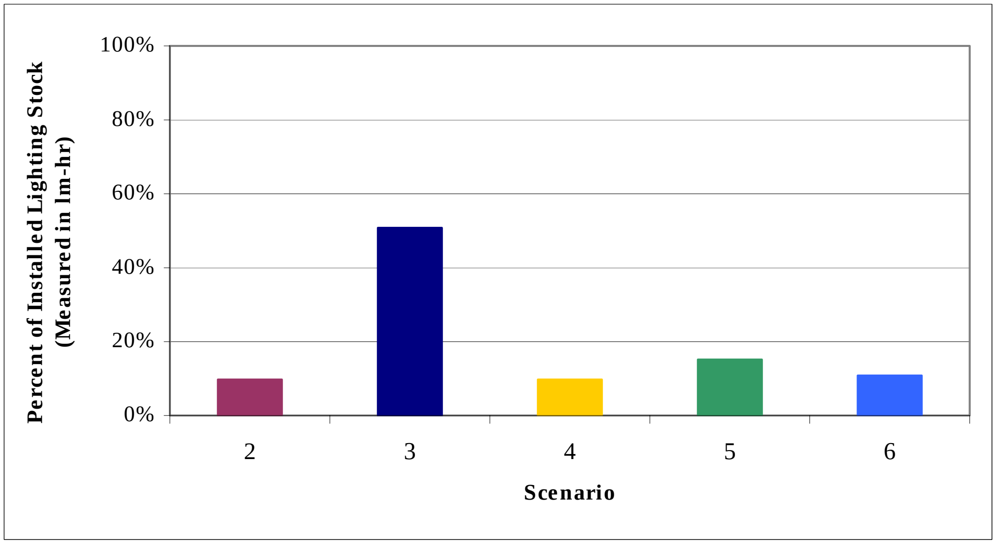
In comparison with Scenario 2 (Medium R&D), Scenario 5 (Medium R&D, Plus Rebate) is particularly effective in generating earlier CO_2 emission reductions. Scenario 6 on the other hand is able to accelerate the rate at which emission reductions are generated. Scenario 5 (Medium R&D, Plus Electricity Tax) on the other hand is the least effective in affecting the outcome of CO_2 emissions.

4. SSL Market Penetration

By 2025 the overall percent of the lighting stock (in terms of Tlm-hr) that is held by SSL, varies among the different policy scenarios as shown in Figure IV-4. In Scenario 3 (Advanced R&D), SSL represents 51% of the total installed stock of lighting by 2025. In Scenario 2 (Medium R&D), the SSL share of the lighting stock is quite a bit lower at only 10%. This percentage is slightly higher in Scenarios 4, 5 and 6 – which corresponds to the incremental impact of their additional policies (electricity tax, rebate and information program, respectively) above and beyond the medium R&D investment. In these three scenarios, SSL becomes between 10 and

15% of the installed lighting stock by 2025. Out of these three policies, the rebate (Scenario 5) is able to provide the largest percent of installed SSL lighting by 2025.

Figure IV-4. Percent of Commercial Lighting Stock that is SSL in 2025

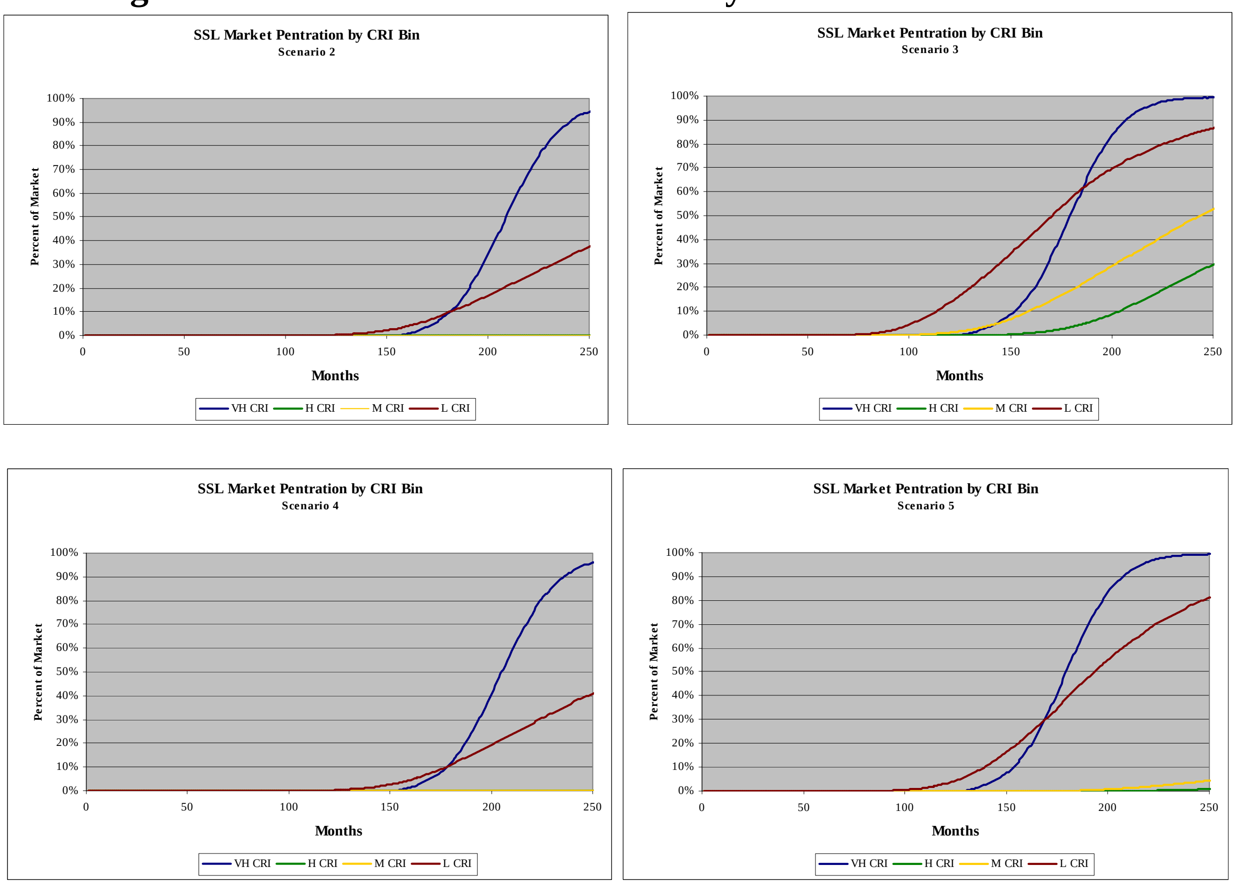


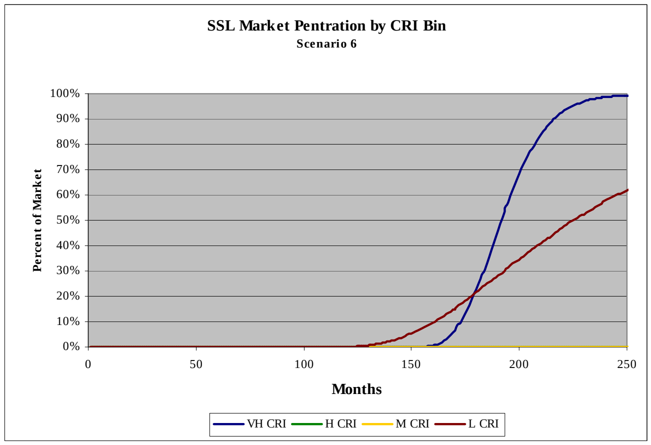
In Scenario 2, the lighting market shifts rather dramatically so that 51% of the lumen-hours are supplied by SSL in 2025. For policy purposes, it is important to analyze how and when different groups (bins) of commercial building sector lighting convert from CL to SSL. This will facilitate a better understanding of which segments of the commercial lighting market will be early adopters, and which CRI bins generate the greatest energy and CO_2 savings. Subsequently, high impact CRI bins can be focused on in an effort to gain the greatest CO_2 emission reductions.

The market penetration under all five policy scenarios is depicted in Figure IV-5. The market penetration is shown in months, in which 151 months are equivalent to the 21-year time span from 2005 until 2025. The market penetration is represented by the percent of lumen-hours that are supplied by SSL. All of the SSL curves follow the stylized s-curve of diffusion. In all scenarios, by 2025 the VH CRI bin is almost completely dominated by SSL; the s-curves have all reached their asymptotic limit of approximately 95-99%. Earlier in the chapter, Figure IV-2 showed that in all five policy scenario, the VH CRI bin was responsible for the majority of annual energy savings in 2025. Hence, it is the market penetration of the VH CRI that is driving these energy/ CO_2 emission reductions.

Interestingly, SSL in the L CRI also attains a significant share of the SSL by 2025 in all five of the policy scenarios shown in Figures IV-5-10. However, this market penetration doesn't generate significant energy savings. For instance, in Scenario 2, SSL captures about 38% of the L CRI bin by 2025; however this bin only accounts for only 1% of total energy savings.

Figure IV-5. SSL Market Penetration by CRI Bin: Five Scenarios





The high energy savings from the VH CRI bin arises from the fact that SSL penetrating the VH CRI bin is much more efficacious than the average CL technology. Hence, the energy savings from SSL penetration are more significant in this bin. The difference in the efficacies of SSL and CL in the L CRI bin are much less striking, and thus the energy and CO_2 emissions impact from SSL penetration is comparatively much less. Furthermore, while the VH CRI bin consumed approximately 30% of commercial building energy for lighting in 2005, the L CRI bin consumed only about 3%. Hence, SSL market penetration in the VH CRI bin is able to reduce energy use more than SSL penetration into the L CRI bin.

In all five scenarios shown in Figure IV-5, SSL market penetration first occurs in the L CRI bin. In Scenario 3, L CRI SSL begins to penetrate the market in month 80 (approximately year 2012). In Scenario 2, L CRI SSL begins to penetrate the market in month 125 (approximately 2015). The rebate is able to stimulate earlier market penetration in the bin, moving market penetration from 125 to month 90, accelerating market penetration by about 3 years.

In Scenario 3 (Advanced R&D), all four CRI bins see significant SSL market penetration by 2025. By this year, SSL captures: 99% of VH CRI lighting; 31% of H CRI lighting; 54% of M CRI lighting; and 87% of L CRI lighting.

It is noticeable in all scenarios depicted in Figure IV-5, that the *rate* of VH CRI market penetration is much quicker than in the other CRI bins. This can be attributed to the rapid turnover of CL in the VH CRI bin. For example, in 2005 average lifetime of a VH CRI CL is 2,600 hours whereas the average lifetime of L CRI CL is 19,000 hours. Therefore, the retirement turnover rate when the CL lighting technologies reach the end of their useful life is much shorter for VH CRI and this rapid turnover allows the share of SSL to grow more rapidly.[46]

4. Epidemic Effect

An epidemic effect was incorporated into the SSL CMP model to account for the impact that information diffusion through social networks will have the adoption of a SSL technology. The epidemic rate is incorporated into the SSL CMP model as factor that encourages earlier CL retrofits. In the model it is assumed that all of these early retrofits due to the epidemic effect are automatically translated into SSL purchases.

In Table IV-5 the impact from the epidemic effect is presented in terms of the cumulative retrofits undertaken, and how many of these retrofits are attributed to the epidemic effect. (The remaining retrofits are attributed to the normal retrofit rate). The impact that the epidemic effect

[46] It is essential to keep in mind that this model assumes there are no compatibility issues or switching costs (*e.g.*, different lighting fixtures) associated with replacing a CL lighting technologies with a SSL technology.

has in each of the five policy scenarios can be seen from the percentage of retrofits due to the epidemic effect.

Table IV-5. Cumulative Epidemic Effect by Policy Scenario

	Total Cumulative Retrofits	Cumulative Retrofits from Epidemic Effect	% of Retrofits due to Epidemic Effect
	(In Tlm-hr)		
Scenario 2	2120.6	0.00	0.0%
Scenario 3	2127.8	190.7	9.0%
Scenario 4	2116.5	0.00	0.0%
Scenario 5	2099.6	21.3	1.0%
Scenario 6	2104.2	3.45	0.2%

In Scenarios 2 and 4, the epidemic effect doesn't play any role in encouraging SSL diffusion. On the other hand, in Scenario 3 the epidemic effect accounts for 9% of all retrofits that occur over the 21-year time period. In Scenarios 5 and 6 the epidemic rate accounts for a smaller fraction – 1.0 and 0.2% respectively – of the total retrofits that occur between 2005 and 2025.

In Scenarios 3, 5 and 6 the epidemic effect does not play a role in SSL diffusion until a significant share of the installed lighting stock is SSL. This is because the monthly epidemic rate only becomes greater than zero after a minimum of 10% of the lighting market is SSL. In Scenarios 2 and 4, SSL market penetration only attains approximately a 10% market penetration in 2025, and hence the epidemic effect never comes into play. The annual epidemic rate is relatively small (ranges from 0.0 to 5.0%) and hence because the SSL CMP STELLA model only captures outputs of up to two decimal places – in some cases the epidemic effect might be real, but so small it its effect is undetectable. For the purposes of this analysis, these tiny effects are deemed negligible. On the other hand, in Scenario 3 the epidemic effect becomes a fairly significant stimulus for lighting retrofits. Under Scenario 5, 1.0% of CL lighting is retrofitted because of the epidemic effect; a portion of this 1.0% is retrofitted despite the fact that the payback never falls under 10 years (which is the maximum payback for market penetration to begin to occur). In this case, the epidemic effect that results from knowledge and experience about SSL in one bin, spills over and influences purchasing decisions in other bins.

Of the scenarios considered in this thesis, from Table IV-5 it is apparent that the epidemic effect plays the most significant role in lighting retrofit decisions in Scenario 3. This can be attributed to the strong share of the market that SSL is able to capture. Hence, the epidemic effect is seen to have the greatest impact on the number of retrofits when SSL becomes a significant player in the lighting market.

5. Sensitivity Analysis

The sensitivity analysis in this thesis focuses on assumptions made about different policies and certain consumer responses to these policies that are integrated into the SSL CMP model. This sensitivity analysis focuses on the key variables that were used in testing the policies. These variables are adjusted to values 50% higher and lower than the original values. When graphical relationships were used (*e.g.* to relate the years payback to the market share awarded to SSL), the bottom value on the x-axis was increased and then decreased by 50% to perform the sensitivity analysis. Then the SSL CMP model was run and two critical outputs were tracked to determine how sensitive the final outcomes were to the change in the variable. The 2025 annual CO_2 emissions and the cumulative CO_2 emissions were chosen as two model outputs to be tracked.

In Table IV-6, each variable tested in this sensitivity analysis is listed, along with the initial value (the middle value) and upper and lower limited tested, and the changes in the two outcomes for each limit.

Table IV-6. Sensitivity Analysis for Select Variables
(Performed Using Scenario 2)
(MMT CO_2)

Variable	Value	Cumulative CO_2 (Change from Base)		CO_2 emissions in 2025 (Change from Base)	
Electricity Tax	5%	5,835.4	0.2%	248.1	0.3%
	10%	5824.0		247.4	
	15%	5,813.3	0.2%	246.8	0.2%
Rebate	25%	5,450.9	3.2%	238.8	1.3%
	50%	5,659.4		241.9	
	75%	5,768.2	1.9%	244.7	1.2%
Information Program*	Lower	5,668.1	1.3%	242.6	0.3%
	Medium	5,744.0		243.4	
	Upper	5,901.5	2.7%	251.2	3.2%
Epidemic Rate**	Lower	5,847.2	0.0%	248.9	0.0%
	Medium	5,847.2		248.9	
	Upper	5,846.6	0.0%	248.6	0.1%

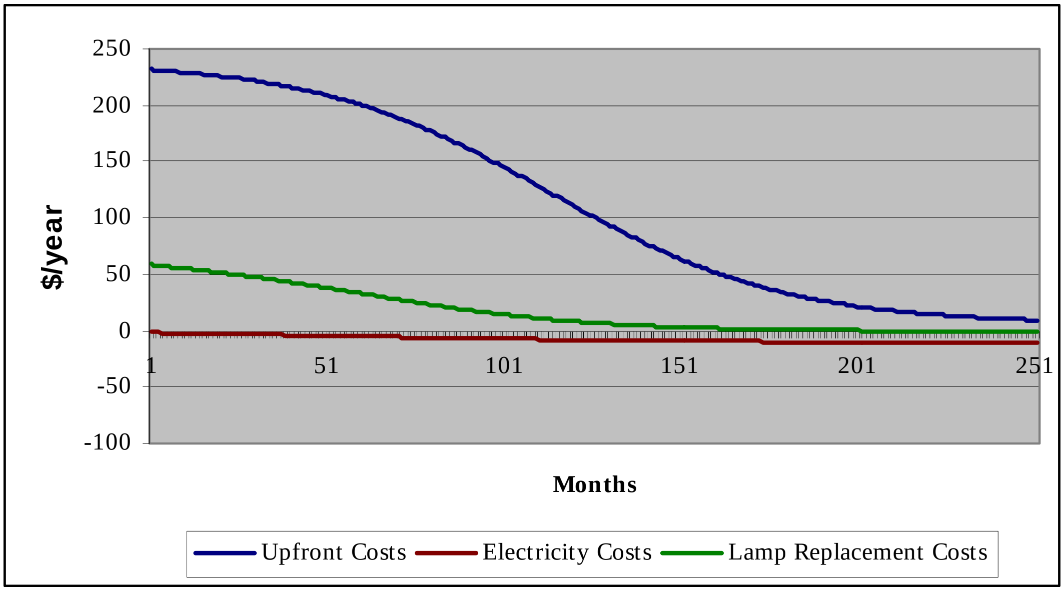
Note: All of the sensitivity runs were performed assuming a Medium R&D Investment.
* The lower and upper limits were established for information program graph, by changing the value of the x-axis from 10 to 5 and from 10 to 15, respectively.
** The lower and upper limits for the epidemic rate graph were established by changing the value of the x-axis from 1 to 1.5, and 1 to .5, respectively.

According to the sensitivity analysis, the rebate and information program are the most sensitive variables. For the rebate, the cumulative emissions of CO_2 are changed by either 1.9 or 3.2% from the base value; the 2025 annual CO_2 emissions are affected by 1.2-1.3%. For the information program, the cumulative emissions of CO_2 have a changed by either 1.3 or 2.7%; the 2025 annual CO_2 emissions are affected by either 0.3 or 3.2%. For both the rebate and information program, cumulative CO_2 emissions outcomes tended to exhibit higher sensitivity.

This would be expected because changes in the values of the rebate and information program would change the shape of the emission curve; and the cumulative impact of a number of years is likely to be more significant that final annual emissions in 2025.

The electricity tax exhibited relatively little sensitivity – the base value of 2025 annual emissions was changed by just 0.2-0.3%. The epidemic rate is even less sensitive; the impact on the 2025 annual emissions is too small to capture in million metric tons (measured to a tenth of a million metric ton). That the electricity tax was not particularly sensitive was not surprising, because of the relatively small impact that the price of electricity has on the payback calculation, which subsequently determines the percent of the market captured by SSL. In Figure IV-6 below, the electricity cost, the upfront cost and the lamp replacement costs are plotted over 20 years for the VH CRI bin (under Scenario 2). Each of these costs represents the different in the cost between SSL and CL; the annual difference in the electricity costs falls from -$1.64 to -$10.74. Comparatively the cost of electricity has much less impact that the other two components of the payback calculation, which explains why electricity tax was found to be a relatively insensitive variable.

Figure IV-6. Payback Calculation Components (VH CRI Bin)



On the other hand, the insensitivity of the epidemic rate was somewhat a surprise. One of the most widely use conceptual models of technology diffusion is based on the epidemic effect, and accordingly, it was expected that the epidemic variable would have a relatively significant impact on SSL diffusion. Several explanations may account for the lack of sensitivity witnessed in this analysis. First, while the relationship in which a higher market share of SSL creates a higher epidemic rate of retrofits – the assumption that this rate would extend only up to 5% a year when 100% SSL market penetration was attained, might be too modest. Furthermore, since in Scenario 2 (which was used as the reference case for the sensitivity analysis) the SSL market penetration only reaches approximately 10%, the epidemic effect never became a significant cause of retrofits.

Third, in the SSL CMP model the epidemic effect only has an impact on the number of monthly retrofits. However, the epidemic effect could also increase the likelihood that SSL is purchased when new buildings are constructed or when old equipment is retired at the end of its life.

Hence, the impact of the epidemic effect could be understated in this model. As will be discussed in the final chapter, future work could focus on clarifying the relationship between the epidemic effect and the diffusion of new lighting technologies so that the epidemic effect could be more accurately integrated into the SSL CMP model.

Since the information program and rebate are relatively sensitive variables in this analysis relative to the electricity tax and the epidemic effect, it is important to discuss the implications this sensitivity has on some of the final results. The rebate was implemented in Scenario 5 and the information program was implemented in Scenario 6. According to Table IV-6, approximately 242 and 243 MMT of CO_2 is emitted annually under Scenario 5 and 6, respectively, in the year 2025. These emissions represent annual CO_2 emission reductions of 81.5 and 80.0 MMT CO_2, respectively, from Reference Scenario 1. Annual CO_2 emissions were found to vary respectively by 1.2 – 1.3% when analyzing the sensitivity of the rebate, and 0.3 – 3.2% when analyzing the sensitivity of the information program. Thus, despite sensitivity of the rebate and information program – even when taking into account their sensitivity ranges they still generate net reductions in emissions.

CHAPTER V. CONCLUSION

1. Overview of Analysis

Solid-state lighting is an emerging energy-efficient lighting technology. This thesis has explored the potential of SSL to provide a reduction in carbon dioxide (CO_2) emissions when deployed in the commercial building sector for general illumination. This thesis has also explored how public policy mechanisms can accelerate the diffusion of SSL and the subsequent impact this has on primary energy consumption and CO_2 emissions.

This analysis was conducted by building an economic-energy-environment dynamic simulation model, entitled the SSL CMP model. This model was built using the STELLA systems modeling software tool to simulate the market penetration of SSL into the general lighting market in the U.S. commercial building sector. Modeling with STELLA provides a unique advantage in that it allows the user to gain a better understanding of the dynamics of a complex system. The model simulation allows for a clear accounting of feedback, dynamics, and consequences from policy decisions. This model is unique in that the STELLA modeling software allows for a comprehensive systems approach to modeling the process of technology diffusion. The SSL CMP model is also a richer model because it integrates epidemic-type effects to simulate how a technology is diffused through the market.

2. Summary of Results & Policy Recommendations

The primary findings from this research are summarized below:

- **Deploying SSL in the commercial building sector offers the potential for up to a 45% reduction in primary energy-use and CO_2 emissions by 2025.** Scenario 3 which is the accelerated R&D scenario generates a 45% annual reduction of emissions reduction from the Reference Scenario. Scenario 2 (Medium R&D) on the other hand generates a 23% annual reduction of emissions in 2025 from the Reference Scenario, with Scenarios 4 through 6 providing incremental reductions of 1-3%. However these energy and CO_2 emission reductions do not appear until *at least* 2015. In light of this, it is apparent that SSL used for general illumination applications should not be considered a near-term solution to reduce CO_2 emissions.

- **Technical improvements and cost reductions on solid-state lighting are important for realizing continuous CO_2 emission reductions.** In this model, it is assumed that a higher level of R&D will generate greater cost reductions and performance improvements. This allows SSL to become competitive with CL at an earlier point in time, and in more CRI bins of the commercial lighting market. By 2025, emissions under Scenario 3 are still continuously falling because SSL achieves early market penetration in the VH and L CRI bins, and later achieves market penetration in the M and H CRI bins. Because new markets are continuously being opened up and penetrated, emissions reductions continue to fall through 2025. In contrast, under Scenarios 2, 4, 5, and 6 – SSL achieves fairly significant market penetration in the VH and L CRI bins but is not able to break into and gain substantial market penetration in the M and H CRI bins. Therefore, emission reductions (and energy reductions) under these scenarios begin to plateau around 2023-2024.

- **A rebate on SSL can stimulate earlier market adoption, and an information program can enhance the rate at which SSL diffuses through the market.** The additional policies (electricity tax, SSL rebate, and information program) which are used in conjunction with a medium R&D investment in Scenarios 4, 5, and 6, respectively, are only able to achieve moderate incremental benefits over Scenario 2 (Medium R&D). Of these three policies, the rebate is able to generate earlier CO_2 emission reductions because the upfront price of SSL equipment is reduced making it more competitive with CL technology. The information program on the other hand, generates a more rapid rate of CO_2 emission reductions because it is able to accelerate the rate at which SSL penetrates the market. The electricity tax on the other hand provides only a very small improvement in CO_2 emission reductions from Scenario 2. Hence, a rebate program appears to be the most effective way to achieve an early market penetration, while the information program can be an effective program in speeding up the rate at which SSL is diffused through the market.

- **Earlier emission reductions occur under the higher national R&D investment scenario.** The earliest market penetration of SSL occurs is in Scenario 3 (Advanced R&D), and creates a 13% cumulative CO_2 emission reduction between 2005 and 2025, relative to the Reference Scenario. Scenario 2 (Medium R&D) on the other hand only generates a cumulative reduction of 4.5%. Of the three additional policy mechanisms that were tested in this analysis, the rebate generates the highest cumulative emission reduction of 7.6% from the Reference Scenario.

- **The majority of CO_2 emissions in all five policy scenarios are generated from replacing incandescent lighting.** This is in part due to the much higher efficiency of SSL compared to the incandescent CL technology it replaces in the VH CRI bin. Furthermore, VH CRI accounted for approximately 30% of total lighting energy consumption in 2005, while L CRI lighting accounted for just 3%; therefore even if SSL displaces a significant percentage of CL in the L CRI bin, the energy savings are smaller than if the same percentage of conventional VH CRI lighting is displaced. For example, in Scenario 2, by 2025 SSL has penetrated 95% of the VH CRI bin and 38% of the L CRI bin. However, 99% of the total energy savings accrue from VH CRI bin and only 1% of energy reductions accrue from the L CRI bin. This implies that substantially more emission reductions can be achieved by focusing on replacing incandescent lamps that compose the VH CRI bin, with SSL. However, at the same time if CFL continue to gain market share by replacing incandescent lamps, then SSL will not only face a better performing incumbent technology, but the CO_2 benefits reaped from replacing CFLs with SSL will be smaller.

Although this thesis does not focus on the residential sector, it is also worth noting that VH CRI lighting is also widely used in the residential sector. In fact, VH CRI incandescent lighting in the residential sector consumes approximately 90% of the household energy used for lighting (DOE, 2002). Therefore, because replacing incandescent VH CRI lighting with

SSL is the most substantial energy savings in the commercial sector, the residential sector is also likely to be an important target for SSL market penetration.

- **The epidemic rate has the most significant impact when a significant portion of the market is captured by SSL.** The epidemic effect in the SSL CMP model had the most impact under Scenario 3; in which SSL gains over a 50% share in the lighting market by 2025. Under this scenario, because SSL achieves significant market penetration, a greater percentage of retrofits are undertaken to replace CL with SSL. Intuitively, this finding seems almost self-evident; however incorporating this epidemic into technology diffusion models and policy planning has important implications. Public policy can be used to build an early market for a new technology, thereby "infecting" a base of users, and then relying on market mechanisms and the epidemic dynamic of technology diffusion to take over and finish the diffusion process.

Although all models are based on simplifying assumptions which are made to reduce the problem or situation to a manageable complexity, one assumption in particular is important to mention because of the model results. The results are predicated on the assumption that SSL will fit into existing lighting sockets. If this is not the case, and there are significant switching costs, SSL will experience slower market penetration. Only lighting systems that are newly built or are totally replaced could be potentially replaced by SSL. This is a particularly important assumption, because so much of the energy and CO_2 savings is found to accrue by replacing incandescent lighting, in which the short lifetime (~1,000 hours) means that these lamps are frequently replaced. Hence, SSL that are made to fit into the typical Edison-sockets would need to be widely available, with the appropriate electronics to modify the electricity from alternating current to direct current.

This thesis has quantified some of the benefits following the development and market penetration of SSL for general illumination into the commercial building sector. Although the policy scenarios tested were not exhaustive, they provide guidance as to how different policy mechanisms can impact the rate of SSL diffusion and the subsequent CO_2 emission reductions that can be achieved. From the primary findings highlighted above, a suite of policy options have been selected.

Policy Recommendations:

1. The government should invest in SSL R&D so as to realize the accelerated performance and cost targets for SSL. This investment should be supplemented by a coordinated effort to offer rebates early in the diffusion process, after SSL enters the market for general illumination.
2. In the near-term, focus should be concentrated on developing and deploying SSL as a viable and attractive replacement for incandescent lighting. In the longer-term, greater focus should be placed on developing SSL products that capitalize on the innovativeness of SSL – but might not be feasible direct replacements for incandescent lamps in conventional Edison fixtures.
3. An information program (*e.g.,* ENERGY STAR) should be used to label high-quality SSL products, in order to accelerate market penetration.

2. Areas for Future Research

An important complement to this research would estimate the costs associated with these types of programs and policies that can accelerate the market penetration of SSL. Furthermore, additional work is needed to quantify some of the additional benefits from developing energy-efficient SSL. Some of these benefits include environmental and health benefits that accompany reducing energy use (*e.g.*, air pollution, mining and drilling for fossil fuels, land needed for the sitting of new power plants); the economic benefits from developing a strong and innovative SSL industry in America (*e.g.* new job creation); the occupational benefits from deploying high quality SSL into the workplace (*e.g.* higher productivity); and the additional energy impacts that SSL can have by affecting the energy required for space conditioning or through reducing peak load energy-demand.

Further research could focus on expanding the SSL CMP model by integrating a greater degree of complexity; including the fixture costs and lifetimes of conventional lighting, a more detailed stock of lighting technologies, and some of the latest energy-economic modeling techniques for better modeling of consumer behavior. Given the availability of appropriate lighting data, relatively simple adjustments to the SSL CMP model could be made to study the impacts of SSL diffusion on state or regional energy demand. Finally, additional scenarios could also be created and tested using the SSL CMP model. For example, one such scenario could investigate how long rebate a policy should be used early on in the diffusion process, in order to gain a large enough base of “infected” technology users such that the epidemic dynamic could replace the effect the rebate has in stimulating technology diffusion.

Exploring the impact that SSL would have on energy and CO_2 emissions if SSL technologies are not mass-produced to fit into conventional lighting fixtures would be another interesting avenue of research. In other words, SSL would instead replace the current "bulb" culture with more innovative and unique ways of delivering lighting service. Under this scenario, SSL would likely have a much smaller impact in the next 20 years because SSL would predominately be purchased only through new builds or lighting retrofits.

Since the information program variable was found be a sensitive variable, it is recommended that future research concentrate on quantitatively linking information programs with changes in consumer implicit discount rates (and hence, the payback curve). Furthermore, future empirical research over how the epidemic effect changes the rate of diffusion of new lighting technologies (or new energy-efficient equipment in general) could further enhance the SSL CMP model.

Solid-state lighting is an innovative, and highly promising energy-efficient lighting technology. The CO_2 emission reductions that are possible from SSL combined with growing public concern over future implications of global climate change form a compelling case for U.S. public policy intervention to develop and deploy SSL. Over the next decade, research and development with improve the performance and lower costs of SSL, which will allow SSL to become competitive with CL technologies. Solid state lighting holds the potential to reduce CO_2 emissions and primary energy use, and this analysis shows that performance improvements and cost reduction, created through R&D, will be vital be one of the most vital policies for SSL to achieve widespread market penetration in the commercial building sector. While the private sector has an critical role in the R&D process for SSL, the government can aid in this effort by providing funding for research, creating industry roadmaps that define major challenges, and facilitating a private-public partnership.

The rebate program and information program have comparatively less impact on SSL diffusion than greater cost reductions and technology improvements. However, these policies can have some impact. This analysis elucidated that rebates can stimulate earlier SSL adoption and an information program can accelerate the rate of diffusion. Future analysis is needed to estimate additional benefits and costs associated with policies intended to tune the rate of SSL diffusion; if net social benefits are found then the case for government action would be further strengthened. The SSL CMP model has estimated the energy and CO_2 emission benefits from SSL diffusion, and can provide a future platform for estimating further costs and benefits associated with different policy mechanisms.

CHAPTER VI. REFERENCES

CHAPTER VII.

CHAPTER VIII. Alic, J. A., Mowery, D. C., & Rubin, E. S. (2003). *U.S. technology and innovation policies: Lessons for Climate Change*: Prepared for the Pew Center on Global Climate Change.

CHAPTER IX. Arrow, K. J. (1962). Economic welfare and the allocation of resources to invention. In R. R. Nelson (Ed.), *The Rate and Direction of Inventive Activity*. New York: Princeton University Press.

CHAPTER X. Atkinson, B., Denver, A., McMahon, J. E., Shown, L., & Clear, R. (1995). Energy-Efficient Lighting Technologies and Their Appliations in the Commercial and Residential Sectors. In F. Kreith & R. E. West (Eds.), *CRC Handbook of Energy Efficiency* (pp. 399-427). Boca Raton, FL: CRC Press.

CHAPTER XI. Atkinson, B., McMahon, J. E., Mills, E., Chan, P., Eto, T., Jennings, J., et al. (1992). *Analysis of Federal Policy Options for Improving U.S. Lighting Energy Efficiency: Commerical and Residential Buildings* (No. LBL-31469). Berkeley CA.

CHAPTER XII. Bierman, A. (1998). *Lighting Futures- LEDs: From Indicators to Illumination?* Retrieved July 15, 2004, from http://www.lrc.rpi.edu/programs/Futures/LF-LEDs/index.asp

CHAPTER XIII. Brown, M. A. (2001). Market failures and barriers as a basis for clean energy policies. *Energy Policy, 29*(14), 1197-1207.

CHAPTER XIV. Bullough, J. D. (2003). *Lighting Answers: LED Lighting Systems*. Retrieved July 15, 2004, from http://www.lrc.rpi.edu/programs/NLPIP/lightingAnswers/led/abstract.asp

CHAPTER XV. Calwell, C., & Zugel, J. (2003). Laying the Foundation for Market Transformation. *Home Energy, 20.3*.

CHAPTER XVI. Decanio, S. J., & Laitner, J. A. (1997). Modeling technological change in energy demand forecasting: A generalized approach. *Technological Forecasting and Social Change, 55*(3), 249-263.

CHAPTER XVII. **DOE. (2001).** ***Energy Savings Potential of Solid State Lighting in General Lighting Applications*. Washington, DC: Prepared by Arthur D. Little, Inc. for the U.S. Department of Energy, Office of Building Technology, State and Community Programs.**

CHAPTER XVIII. **DOE. (2002).** ***U.S. Lighting Market Characterization Volume I: National Lighting Inventory and Energy Consumption Estimate*. Washington, D.C.: Prepared by Navigant Consulting, Inc.for the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy Building Technologies Program.**

CHAPTER XIX. **DOE. (2003a).** ***Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications*. Washington. DC: Prepared by Navigant Consulting, Inc. for the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy Building Technologies Program.**

CHAPTER XX. **DOE. (2003b).** ***Energy Savings Potential of Solid State Lighting in General Illumination Applications*. Washington, DC: Navigant Consulting, Inc.,.**

CHAPTER XXI. **DOE. (2004).** ***Illuminating the Challenges- Solid State Lighting Program Planning Workshop Report*. Washington, DC: Prepared by Navigant Consulting, Inc. for the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy Building Technologies Program.**

CHAPTER XXII. **Drenner, T., Roland Haitz, Jeffery Tsao. (2001).** ***A Market Diffusion and Energy Impact Model for Solid-State Lighting*: Sandia National Laboratory.**

CHAPTER XXIII. **EIA. (2003a).** ***Emissions of Greenhouse Gases in the United States 2002* (No. DOE/EIA-0573(2002)). Washington, DC: U.S. Department of Energy, Energy Information Administration Office of Integrated Analysis and Forecasting.**

CHAPTER XXIV. **EIA. (2003b).** ***The National Energy Modeling System: An Overview* (No. DOE/EIA-0581). Washington, DC: U.S. Department of Energy, Energy Information Administration Office of Integrated Analysis and Forecasting.**

CHAPTER XXV. **EIA. (2004a).** ***Annual Energy Outlook 2004 with Projections to 2025* (No. DOE/EIA-0383(). Washington, DC: U.S. Department of Energy, Energy Information Adminstration Office of Integrated Analysis and Forecasting.**

CHAPTER XXVI. **EIA. (2004b).** ***Electric Power Monthly, Table 1.2 Net Generation by Energy Source: Electric Utilities, 1990 through February 2004*. Retrieved July 26, 2004, from http://www.eia.doe.gov/cneaf/electricity/epm/table1_2.html**

CHAPTER XXVII. **EIA. (2004c).** ***Electric Power Monthly: Electricity Generation, Table 1.1 Net Generation by Energy Source: Total (All Sectors), 1990 through December 2003*. Retrieved April 27, 2004, from http://www.eia.doe.gov/cneaf/electricity/epm/epm_sum.html**

CHAPTER XXVIII. **EPA. (1997).** ***Climate Change and New York* (No. 230-F-97-008ff). Washington, DC: U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation.**

CHAPTER XXIX. **EPA. (2000).** ***Global Warming Impacts*. Retrieved October 2, 2004, from http://yosemite.epa.gov/OAR/globalwarming.nsf/content/Impacts.html**

CHAPTER XXX. **EPA. (2002).** ***In Brief: The U.S. Greenhouse Gas Inventory* (No. 430-F-02-008). Washington, DC: U.S. Environmental Protection Agency, Office of Atmospheric Programs.**

CHAPTER XXXI. **EPA. (2004).** ***Global Warming - Emissions: International*. Retrieved September 29, 2004, from http://yosemite.epa.gov/oar/globalwarming.nsf/content/EmissionsInternational.html**

CHAPTER XXXII. **Geller, H., & Nadel, S. (1994).** ***Market Transformation Strategies to Promote End-Use Efficiency*. Washington, DC: American Council for an Energy-Efficient Economy.**

CHAPTER XXXIII. **Geroski, P. A. (2000). Models of Technology Diffusion. *Research Policy, 29*, 603-625.**

CHAPTER XXXIV. **Griliches, Z. (1957). Hybrid Corn: An Exploration in the Economics of Technological Change. *Econometrica, 25*, 501-522.**

CHAPTER XXXV. **Haitz, R., Kish, F., Tsao, J., & Nelson, J. (2000).** ***Another Semiconductor Revolution: This Time It's Lighting!* Retrieved November 16, 2004, from http://lighting.sandia.gov/lightingdocs/HaitzR200003.pdf**

CHAPTER XXXVI. **Interlaboratory Working Group. (2000).** ***Scenarios for Clean Energy Future*. Oak Ridge, TN and Berkeley, CA: Oak Ridge National Laboratory and Berkely National Laboratory.**

CHAPTER XXXVII. **IPCC. (1996).** ***Climate Change 1995: The Science of Climate Change*. Cambridge, UK: Cambridge University Press.**

CHAPTER XXXVIII. IPCC (Ed.). (2001). *Climate Change 2001: A Synthesis Report*. Cambridge, UK: Cambridge University Press.

CHAPTER XXXIX. Jaffe, A. B., & Stavins, R. N. (1991). *Evaluation of the Relative Effectiveness of Economic Incentives and Direct Regulation for Environmental Protection: Impacts on the Diffusion of Technology. CSIA Discussion Paper No 91-1*: Center for Science & International Affairs, Harvard University.

CHAPTER XL. Jaffe, A. B., & Stavins, R. N. (1994a). The energy paradox and the diffusion of conservation technology. *Resource and Energy Economics, 16*(2), 91-122.

CHAPTER XLI. Jaffe, A. B., & Stavins, R. N. (1994b). The energy-efficiency gap. *Energy Policy, 22*(10), 804-810.

CHAPTER XLII. Johnson, S. (2000). The Solid State Lighting Initiative: An Industry/DOE Collaborative Effort. *Architectural Lighting*(Nov./Dec.).

CHAPTER XLIII. Koomey, J. G., Sanstad, A. H., & Shown, L. J. (1996). Energy efficient lighting: Market data, market imperfections, and policy success. *Contemporary Economic Policy, 14*(3), 98.

CHAPTER XLIV. Lutzenhiser, L. (1994). Innovation and organizational networks. *Energy Policy, 22*(10), 867-876.

CHAPTER XLV. Mansfield, E. (1968). *Industrial Research and Technological Innovation: An Econometric Analysis*. New York, NY: W.W. Norton & Company.

CHAPTER XLVI. Martin, P. S. (2001, September). The future looks bright for solid-state lighting. *Laser Focus World*.

CHAPTER XLVII. Menanteau, P., & Lefebvre, H. (2000). Competing technologies and the diffusion of innovations: the emergence of energy-efficient lamps in the residential sector. *Research Policy, 29*(3), 375-389.

CHAPTER XLVIII. Mills, E. (1995). *Energy-Efficient Lighting Policies and Programs from the United States Government.* Paper presented at the 2^{cd} International Lighting Conference, Suzdal, Russia.

CHAPTER XLIX. Nadel, S., & Geller, H. (1996). Utility DMS, What have we learned? Where are we going? *Energy Policy, 24*(4), 289-302.

CHAPTER L. NRC. (2001). *Climate Change Science: An Analysis of Some Key Questions*. Washington, DC: National Academies Press.

CHAPTER LI. NRC. (2002). *Partnerships for Solid-State Lighting: Report of a Workshop*. Washington, DC.

CHAPTER LII. OTA. (1992). *Building Energy Efficiency*. Washington, DC: U.S. Congress, Office of Technology Assessment.

CHAPTER LIII. OTA. (1993). *Energy Efficiency: Challenges and Opportunities for Electric Utilities*. Washington, DC: U.S. Congress, Office of Technology Assessment.

CHAPTER LIV. Poortinga, W., Steg, L., Vlek, C., & Wiersma, G. (2003). Household preferences for energy-saving measures: A conjoint analysis. *Journal of Economic Psychology, 24*(1), 49-64.

CHAPTER LV. The Promise of Solid State Lighting for General Illumination: Light Emitting Diodes (LEDs) and Organic Light Emitting Diodes (OLEDs). (2001). *Conclusions and Recommendations from OIDA Technology Roadmaps*. Washington, DC: Optoelectronics Industry Development Association.

CHAPTER LVI. Rogers, E. M. (1995). *Diffusion of Innovations* (Fourth ed.). New York, NY: The Free Press.

CHAPTER LVII. Romig, A. (2002). Advanced Energy Technology Development in NM, *Testimony given before the U.S. Senate Energy Committee*. Albuquerque, NM.

CHAPTER LVIII. Sandia National Laboratory. (2003). *Press Release: Sandia researchers use quantum dots as a new approach to solid-state lighting*. Retrieved August 9, 2004, from http://www.sandia.gov/news-center/news-releases/2003/elect-semi-sensors/quantum.html

CHAPTER LIX. Stern, P. C. (1986). Blind Spots in Policy Analysis: What Economics Doesn't Say About Energy Use. *Journal of Policy Analysis and Management, 5*(2), 200-227.

CHAPTER LX. Stokey, E., & Zeckhauser, R. (1978). *A Primer for Policy Analysis*. New York, NY: W.W. Norton & Company.

CHAPTER LXI. Stoneman, P., & Diederen, P. (1994). Technology Diffusion and Public Policy. *The Economic Journal, 104*(425), 918-930.

CHAPTER LXII. **Ton, M., Foster, S., Calwell, C., & Conway, K. (2003).** ***LED Lighting Technologies and Potential for Near-Term Applications*** **(No. E03-114): Prepared by Ecos Consulting for Northwest Energy Efficiency Alliance.**

CHAPTER LXIII. **Tsao, J. (2004). Solid-State Lighting: Lamps, Chips and Materials for Tomorrow.** ***IEEE Circuits & Devices Magazine, May/June 2004*****.**

CHAPTER LXIV. **Tsao, J. (Ed.). (2002).** ***Light Emitting Diodes (LEDs) for General Illumination: An OIDA Technology Roadmap Update 2002*****. Washington, DC: Optoelectronics Industry Development Assocation.**

CHAPTER LXV. **Vorsatz, D., Shown, L., Koomey, J., Moezzi, M., Denver, A., & Atkinson, B. (1997).** ***Lighting Market Sourcebook for the U.S.*****: Lawrence Berkeley National Laboratory.**

CHAPTER LXVI. **Wang, M. (1998). The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model (Version 1.4a) [Computer Software]. Argonne, IL: Argonne National Laboratory.**

CHAPTER LXVII. **Wei, J., Zhu, H., & Wu, D. (2004). Carbon nanotube filaments in household light bulbs.** ***Applied Physics Letters, 84*****(24), 4869-4871.**

CHAPTER LXVIII. **Whitaker, T. (2004). Lighting community outlines challenges for LED industry.** ***Compound Semiconductor, March 2004*****.**

CHAPTER LXIX. **Zukauskas, A., Shur, M., & Gaska, R. (2002).** ***Introduction to Solid-State Lighting*****. New York, NY: John Wiley & Sons, Inc.**

CHAPTER LXX. APPENDIX A. Lighting Glossary

Ballast – An electrical device used to control the current provided to a lamp.

[CCT] Color Correlated Temperature – The absolute temperature of a blackbody whose chromaticity most nearly resembles that of the lighting source.

[CRI] Color Rendering Index – A measure of how surface colors appear when illuminated by the lamp, compared to how they appear when illuminated by a reference source of the same temperature.

Efficacy – The energy-efficiency of lighting; calculated by dividing the quantity of light emitted from the lamp (in lumens) by the power input to the lamp (in watts)

General Lighting/General Illumination – Provides the lighting required for performing tasks. This lighting is commonly divided into three categories: *ambient; task* and *accent lighting.* Ambient lighting typically provides securing and safety as well as the lighting needed to perform general tasks. Task lighting provides just enough light so that a particular task can be performed but not enough to illuminate a larger surface. Accent lighting illuminates typically illuminates walls.

Lamp – A generic term for an artificial source of light. In this thesis is it taken to represent the actual electrically powered "bulb" or "tube"; or in the case of SSL, the semiconductor chip, which generates the light.

Lighting Controls – A wide range of technologies that are used to electromechanically and/or mechanically control the lighting in a building.

Lighting Fixture – A housing for securing lamp(s) and ballast(s), and controls the light distribution to a particular area.

Lumen – A basic unit measurement of light. A lumen is defined as the amount of light given out through a solid angle by a source of one candela [unit of luminous intensity] radiating out equally in all directions.

Luminaire – Most commonly used to refer to the complete lighting system that includes a lamp, ballast and fixture.

Watt – A unit of power.

APPENDIX B. Commercial Sector Lamps

Type	Wattage (lm/W)	Efficacy (W)	CRI	Lamp Life in 2005 (khrs)	Lamp Price 2005 ($)	Price in 2005 ($/klm)	Distribution Lamp Output (Tlm-hr)	Percent
Standard - General Service	83	16	100	2.5	1.00		1,114	63%
Standard - Reflector	104	9	100	1.5	2.25		270	15%
Halogen - General Service	64	15	100	2.8	3.50		3	0%
Halogen – Quartz	226	20	100	3.5	3.00		276	16%
Halogen - refl. - low volt	48	11	100	4.0	3.75		80	5%
Low wattage (less than 25W)	15	9	100	2.5	0.65		34	2%
Misc incandescent	0	13	100				-	
INCANDESCENT / VH CRI	**105.5**	**15.2**		**2.6**	**1.62**	**1.01**	**1,777**	
T5	8	50	78	20.0	2.00		13	0%
T8 – less than 4’	23	82	80	17.5	3.00		196	2%
T8 – 4’	33	85	80	17.5	2.00		3,876	49%
T8 – More than 4’	50	88	68	13.8	6.00		29	0%
T8 – U-bent	34	74	80	20.0	7.50		107	1%
T12 – less than 4’	29	63	71	12.8	2.25		202	2%
T12 – 4’	45	74	70	20.0	1.50		8,073	73%
T12 – More than 4’	93	79	76	14.5	3.50		3,076	39%
T12 – U-bent	46	69	67	15.0	5.50		402	4%
Compact – Plug-in	17	60	82	15.0	5.50		391	5%
Compact – Screw base	16	55	82	10.0	5.50		161	2%
Compact – Plug-in – reflector	16	55	82	10.0	8.00		-	
Compact – Screw base – reflector	16	55	82	10.0	8.00		19	0%
Circline	30	58	73	11.0	3.50		164	1%
Induction discharge	0	53	85		2.25		-	0%
Miscellaneous fluorescent	18	60	80	10.0			24	0%
FLUORESCENT / H CRI	**55.0**	**80.4**		**16.0**	**2.94**	**0.67**	**7,863**	100%
FLUORESCENT / M CRI	**129.5**	**71.6**		**18.3**	**1.40**	**0.15**	**11,072**	100%
Mercury vapor	331	40	33	20.0	22.00		261	30%
Metal halide	472	65	68	13.8	60.00		2,202	20%
High pressure sodium	260	104	22	20.0	22.00		587	68%
Low pressure sodium	104	140	10	16.0	22.00		18	2%
Xenon	0	40					-	
Electrodeless (e.g. mercury)	0	150					-	
HID / L CRI	**278.2**	**85.5**		**19.9**	**22.0**	**0.93**	**866**	100%
LED	6	20	0					
Electroluminescent	2	10						

Source:

Type –	(DOE, 2002) Appendix E Table-E5, “Commercial Building Lamp Characteristics”
Wattage –	(DOE, 2002) Appendix E Table-E5, “Commercial Building Lamp Characteristics”
Efficacy –	(DOE, 2002) Appendix E Table-E5, “Commercial Building Lamp Characteristics”
CRI–	(DOE, 2003) Table 2-1 “Average Lamp Wattage, Efficacy, and Color Rendering Index”
Lamp Lifetime –	(DOE, 2003) Table 4-3 “Commercial Sector Conventional Technologies Improvement, 2005 and 2025”
Lamp Price –	(DOE, 2003) Table 4-3 “Commercial Sector Conventional Technologies Improvement, 2005 and 2025”
Price in 2005 –	Calculated into $/kWh using wattage, efficacy, and lamp price.
Percent –	(DOE, 2002) Table 5-8 “Distribution of Lamp-Output (Tlm-hr) per Year by Lamp Type”

APPENDIX C. Units & Conversion Factors

Units

khr	kilohour
klm	kilolumen
klm-hr	kilolumen-hour
kWh	kilowatt-hour
lm	lumen
lm-hr	lumen-hour
MMT CO_2	million metric tons of carbon dioxide
Quad	Quadrillion BTUs (British Thermal Unit)
Tlm-hr	Teralumen-hour
TWh	Terawatt-hour
W	watt
Yr	year

Conversion Factors

1 TWh	=	1×10^9 kWh
CO/CO_2	=	1 / 3.67
Primary Energy/ Site-Use*	=	10,768 BTU/kWh

* Used in (DOE, 2002).

APPENDIX D. SSL CMP Model Code

CL[VH_CRI](t) = CL[VH_CRI](t - dt) + (CL_Purchase[VH_CRI] - CL_Retire[VH_CRI] - Retrofits[VH_CRI]) * dt
INIT CL[VH_CRI] = 163

TRANSIT TIME = varies

INFLOW LIMIT = INF

CAPACITY = INF

CL[H_CRI](t) = CL[H_CRI](t - dt) + (CL_Purchase[H_CRI] - CL_Retire[H_CRI] - Retrofits[H_CRI]) * dt
INIT CL[H_CRI] = 661

TRANSIT TIME = varies

INFLOW LIMIT = INF

CAPACITY = INF

CL[M_CRI](t) = CL[M_CRI](t - dt) + (CL_Purchase[M_CRI] - CL_Retire[M_CRI] - Retrofits[M_CRI]) * dt
INIT CL[M_CRI] = 1037.6

TRANSIT TIME = varies

INFLOW LIMIT = INF

CAPACITY = INF

CL[L_CRI](t) = CL[L_CRI](t - dt) + (CL_Purchase[L_CRI] - CL_Retire[L_CRI] - Retrofits[L_CRI]) * dt
INIT CL[L_CRI] = 85.1

TRANSIT TIME = varies

INFLOW LIMIT = INF

CAPACITY = INF

INFLOWS:

CL_Purchase[VH_CRI] = IF (Information__Factor=0) THEN Tlmhr_Needed[VH_CRI]*(1-Percent__SSL[VH_CRI]) ELSE Tlmhr_Needed[VH_CRI]*(1-Percent__SSL_IF[VH_CRI])
CL_Purchase[H_CRI] = IF (Information__Factor=0) THEN Tlmhr_Needed[H_CRI]*(1-Percent__SSL[H_CRI]) ELSE Tlmhr_Needed[H_CRI]*(1-Percent__SSL_IF[H_CRI])
CL_Purchase[M_CRI] = IF (Information__Factor=0) THEN Tlmhr_Needed[M_CRI]*(1-Percent__SSL[M_CRI]) ELSE Tlmhr_Needed[M_CRI]*(1-Percent__SSL_IF[M_CRI])
CL_Purchase[L_CRI] = IF (Information__Factor=0) THEN Tlmhr_Needed[L_CRI]*(1-Percent__SSL[L_CRI]) ELSE Tlmhr_Needed[L_CRI]*(1-Percent__SSL_IF[L_CRI])
OUTFLOWS:
CL_Retire[VH_CRI] = CONVEYOR OUTFLOW

TRANSIT TIME = (CL_Lifetime[VH_CRI]*1000/hr_per_mt)
CL_Retire[H_CRI] = CONVEYOR OUTFLOW

TRANSIT TIME = (CL_Lifetime[H_CRI]*1000/hr_per_mt)
CL_Retire[M_CRI] = CONVEYOR OUTFLOW

TRANSIT TIME = (CL_Lifetime[M_CRI]*1000/hr_per_mt)
CL_Retire[L_CRI] = CONVEYOR OUTFLOW

TRANSIT TIME = CL_Lifetime[L_CRI]*1000/hr_per_mt
Retrofits[CRI_BINS] = LEAKAGE OUTFLOW

LEAKAGE FRACTION = (Retrofit__Rate+Epidemic__Rate)*2

NO-LEAK ZONE = 50%
Cumulative_CO2(t) = Cumulative_CO2(t - dt) + (CO2_Emissions) * dt
INIT Cumulative_CO2 = 0

INFLOWS:
CO2_Emissions = CO2_per_mt[VH_CRI]+CO2_per_mt[H_CRI]+CO2_per_mt[M_CRI]+CO2_per_mt[L_CRI]
Cumulative_TWhr__delivered(t) = Cumulative_TWhr__delivered(t - dt) + (Delivered__TWhr) * dt
INIT Cumulative_TWhr__delivered = 0

INFLOWS:
Delivered__TWhr = (kWhr[VH_CRI]+kWhr[H_CRI]+kWhr[M_CRI]+kWhr[L_CRI])/10^9
SSL[VH_CRI](t) = SSL[VH_CRI](t - dt) + (SSL_Purchase[VH_CRI] - SSL_retire[VH_CRI]) * dt
INIT SSL[VH_CRI] = 0

TRANSIT TIME = varies

INFLOW LIMIT = INF

CAPACITY = INF

SSL[H_CRI](t) = SSL[H_CRI](t - dt) + (SSL_Purchase[H_CRI] - SSL_retire[H_CRI]) * dt
INIT SSL[H_CRI] = 0

TRANSIT TIME = varies

INFLOW LIMIT = INF

CAPACITY = INF

SSL[M_CRI](t) = SSL[M_CRI](t - dt) + (SSL_Purchase[M_CRI] - SSL_retire[M_CRI]) * dt
INIT SSL[M_CRI] = 0

TRANSIT TIME = varies

INFLOW LIMIT = INF

CAPACITY = INF

SSL[L_CRI](t) = SSL[L_CRI](t - dt) + (SSL_Purchase[L_CRI] - SSL_retire[L_CRI]) * dt
INIT SSL[L_CRI] = 0

TRANSIT TIME = varies

INFLOW LIMIT = INF

CAPACITY = INF

INFLOWS:
SSL_Purchase[VH_CRI] = IF (Information__Factor=0) THEN
Tlmhr_Needed[VH_CRI]*(Percent__SSL[VH_CRI])+Retrofits[VH_CRI]*E&R_Ratio ELSE
Tlmhr_Needed[VH_CRI]*Percent__SSL_IF[VH_CRI]+Retrofits[VH_CRI]*E&R_Ratio
SSL_Purchase[H_CRI] = IF (Information__Factor=0) THEN
Tlmhr_Needed[H_CRI]*Percent__SSL[H_CRI]+Retrofits[H_CRI]*E&R_Ratio ELSE
Tlmhr_Needed[H_CRI]*Percent__SSL_IF[H_CRI]+Retrofits[H_CRI]*E&R_Ratio
SSL_Purchase[M_CRI] = IF (Information__Factor=0) THEN
Tlmhr_Needed[M_CRI]*Percent__SSL[M_CRI]+Retrofits[M_CRI]*E&R_Ratio ELSE
Tlmhr_Needed[M_CRI]*Percent__SSL_IF[M_CRI]+Retrofits[M_CRI]*E&R_Ratio
SSL_Purchase[L_CRI] = IF (Information__Factor=0) THEN
Tlmhr_Needed[L_CRI]*Percent__SSL[L_CRI]+Retrofits[L_CRI]*E&R_Ratio ELSE
Tlmhr_Needed[L_CRI]*Percent__SSL_IF[L_CRI]+Retrofits[L_CRI]*E&R_Ratio
OUTFLOWS:
SSL_retire[VH_CRI] = CONVEYOR OUTFLOW

TRANSIT TIME = IF (Advanced_R&D=0) THEN SSL__MR&D_Lifetime[VH_CRI]*1000/hr_per_mt ELSE SSL_AR&D_Lifetime[VH_CRI]*1000/hr_per_mt
SSL_retire[H_CRI] = CONVEYOR OUTFLOW

TRANSIT TIME = IF (Advanced_R&D=0) THEN SSL__MR&D_Lifetime[H_CRI]*1000/hr_per_mt ELSE SSL_AR&D_Lifetime[H_CRI]*1000/hr_per_mt
SSL_retire[M_CRI] = CONVEYOR OUTFLOW

TRANSIT TIME = IF (Advanced_R&D=0) THEN SSL__MR&D_Lifetime[M_CRI]*1000/hr_per_mt ELSE SSL_AR&D_Lifetime[M_CRI]*1000/hr_per_mt
SSL_retire[L_CRI] = CONVEYOR OUTFLOW

TRANSIT TIME = IF (Advanced_R&D=0) THEN SSL__MR&D_Lifetime[L_CRI]*1000/hr_per_mt ELSE SSL_AR&D_Lifetime[L_CRI]*1000/hr_per_mt
Advanced_R&D = 1
CO2_per_kWhr = EF_Coal*Percent_Coal+EF_NG*Percent_NG+EF_Oil*Percent_Oil+Percent_Nuclear*0+Percent_Other*0
CO2_per_mt[CRI_BINS] = kWhr[CRI_BINS]*CO2_per_kWhr/1e12
Coal_Eff = .35
Combined_Ave___Efficiency = Coal_Eff*Percent_Coal+NG_Eff*Percent_NG+Oil_Eff*Percent_Oil+Other_Eff*Percent_Other+Nuclear_Eff*Percent_Nuclear
Cumulative_Delivered__Quads = Cumulative_TWhr__delivered*(.003412)
Cumulative_Primary__Quads = Cumulative_Delivered__Quads/(Combined_Ave___Efficiency*.92)
Delivered__Quads = Delivered__TWhr*.003412
Diff_Operating__Cost[VH_CRI] = Diff__Electricity__Cost[VH_CRI]+Diff__Lamp__Replacement__Cost[VH_CRI]
Diff_Operating__Cost[H_CRI] = Diff__Electricity__Cost[H_CRI]+Diff__Lamp__Replacement__Cost[H_CRI]
Diff_Operating__Cost[M_CRI] = Diff__Electricity__Cost[M_CRI]+Diff__Lamp__Replacement__Cost[M_CRI]
Diff_Operating__Cost[L_CRI] = Diff__Electricity__Cost[L_CRI]+Diff__Lamp__Replacement__Cost[L_CRI]
Diff_Upfront__Cost[VH_CRI] = IF (Advanced_R&D=0) THEN SSL_MR&D_Upfront_Cost[VH_CRI]*SSL_Rebate__Program-CL_Upfront_Cost[VH_CRI] ELSE SSL_AR&D_Upfront_Cost[VH_CRI]*SSL_Rebate__Program-CL_Upfront_Cost[VH_CRI]
Diff_Upfront__Cost[H_CRI] = IF (Advanced_R&D=0) THEN (SSL_MR&D_Upfront_Cost[H_CRI]*SSL_Rebate__Program-CL_Upfront_Cost[H_CRI])

ELSE (SSL_AR&D_Upfront_Cost[H_CRI]*SSL_Rebate__Program-
CL_Upfront_Cost[H_CRI])
Diff_Upfront__Cost[M_CRI] = IF (Advanced_R&D=0) THEN
(SSL_MR&D_Upfront_Cost[M_CRI]*SSL_Rebate__Program-CL_Upfront_Cost[M_CRI])
ELSE(SSL_AR&D_Upfront_Cost[M_CRI]*SSL_Rebate__Program-
CL_Upfront_Cost[M_CRI])
Diff_Upfront__Cost[L_CRI] = IF (Advanced_R&D=0) THEN
(SSL_MR&D_Upfront_Cost[L_CRI]*SSL_Rebate__Program-CL_Upfront_Cost[L_CRI])
ELSE (SSL_AR&D_Upfront_Cost[L_CRI]*SSL_Rebate__Program-CL_Upfront_Cost[L_CRI])
Diff__Electricity__Cost[VH_CRI] = IF (Advanced_R&D=0) THEN
12*(hr_per_mt*Electricity_Costs*Electricity_Tax*(1/SSL_MR&D_Efficacy[VH_CRI]-
1/CL_Efficacy[VH_CRI])) ELSE
12*(hr_per_mt*Electricity_Costs*Electricity_Tax*(1/SSL_AR&D_Efficacy[VH_CRI]-
1/CL_Efficacy[VH_CRI]))
Diff__Electricity__Cost[H_CRI] = IF (Advanced_R&D=0) THEN
12*(hr_per_mt*Electricity_Costs*Electricity_Tax*(1/SSL_MR&D_Efficacy[H_CRI]-
1/CL_Efficacy[H_CRI])) ELSE
12*(hr_per_mt*Electricity_Costs*Electricity_Tax*(1/SSL_AR&D_Efficacy[H_CRI]-
1/CL_Efficacy[H_CRI]))
Diff__Electricity__Cost[M_CRI] = IF (Advanced_R&D=0) THEN
12*(hr_per_mt*Electricity_Costs*Electricity_Tax*(1/SSL_MR&D_Efficacy[M_CRI]-
1/CL_Efficacy[M_CRI])) ELSE
12*(hr_per_mt*Electricity_Costs*Electricity_Tax*(1/SSL_AR&D_Efficacy[M_CRI]-
1/CL_Efficacy[M_CRI]))
Diff__Electricity__Cost[L_CRI] = IF (Advanced_R&D=0) THEN
12*(hr_per_mt*Electricity_Costs*Electricity_Tax*(1/SSL_MR&D_Efficacy[L_CRI]-
1/CL_Efficacy[L_CRI])) ELSE
12*(hr_per_mt*Electricity_Costs*Electricity_Tax*(1/SSL_AR&D_Efficacy[L_CRI]-
1/CL_Efficacy[L_CRI]))
Diff__Lamp__Replacement__Cost[VH_CRI] = IF (Advanced_R&D=0) THEN
((hr_per_mt/(SSL__MR&D_Lifetime[VH_CRI]*1000)*SSL_MR&D_Upfront_Cost[VH_CRI]*
SSL_Rebate__Program)-
(hr_per_mt/(CL_Lifetime[VH_CRI]*1000)*CL_Upfront_Cost[VH_CRI]))*12 ELSE
((hr_per_mt/(SSL_AR&D_Lifetime[VH_CRI]*1000)*SSL_AR&D_Upfront_Cost[VH_CRI]*S
SL_Rebate__Program)-
(hr_per_mt/(CL_Lifetime[VH_CRI]*1000)*CL_Upfront_Cost[VH_CRI]))*12
Diff__Lamp__Replacement__Cost[H_CRI] = IF(Advanced_R&D=0) THEN
((hr_per_mt/(SSL__MR&D_Lifetime[H_CRI]*1000)*SSL_MR&D_Upfront_Cost[H_CRI]*SS
L_Rebate__Program)-
(hr_per_mt/(CL_Lifetime[H_CRI]*1000)*CL_Upfront_Cost[H_CRI]))*12
ELSE
((hr_per_mt/(SSL_AR&D_Lifetime[H_CRI]*1000)*SSL_AR&D_Upfront_Cost[H_CRI]*SSL_
Rebate__Program)-(hr_per_mt/(CL_Lifetime[H_CRI]*1000)*CL_Upfront_Cost[H_CRI]))*12
Diff__Lamp__Replacement__Cost[M_CRI] = IF (Advanced_R&D=0) THEN
((hr_per_mt/(SSL__MR&D_Lifetime[M_CRI]*1000)*SSL_MR&D_Upfront_Cost[M_CRI]*SS

L_Rebate__Program)-
(hr_per_mt/(CL_Lifetime[M_CRI]*1000)*CL_Upfront_Cost[M_CRI]))*12 ELSE
((hr_per_mt/(SSL_AR&D_Lifetime[M_CRI]*1000)*SSL_AR&D_Upfront_Cost[M_CRI]*SSL
_Rebate__Program)-(hr_per_mt/(CL_Lifetime[M_CRI]*1000)*CL_Upfront_Cost[M_CRI]))*12
Diff__Lamp__Replacement__Cost[L_CRI] = IF(Advanced_R&D=0) THEN
((hr_per_mt/(SSL__MR&D_Lifetime[L_CRI]*1000)*SSL_MR&D_Upfront_Cost[L_CRI])*SS
L_Rebate__Program-(hr_per_mt/(CL_Lifetime[L_CRI]*1000)*CL_Upfront_Cost[L_CRI]))*12
ELSE
((hr_per_mt/(SSL_AR&D_Lifetime[L_CRI]*1000)*SSL_AR&D_Upfront_Cost[L_CRI])*SSL_
Rebate__Program-(hr_per_mt/(CL_Lifetime[L_CRI]*1000)*CL_Upfront_Cost[L_CRI]))*12
E&R_Ratio = Epidemic__Rate/(Retrofit__Rate+Epidemic__Rate)
EF_Coal = 1012.3
EF_NG = 562.9
EF_Oil = 896.6
Electricity_Tax = 1
hr_per_mt = 248
Information__Factor = 0
Klmhr_per_sqft_ = 307/12
kWhr[CRI_BINS] = IF (Advanced_R&D=0) THEN
CL[CRI_BINS]*((1/CL_Efficacy[CRI_BINS])*10^9)+SSL[CRI_BINS]*((1/SSL_MR&D_Effic
acy[CRI_BINS])*10^9) ELSE
CL[CRI_BINS]*((1/CL_Efficacy[CRI_BINS])*10^9)+SSL[CRI_BINS]*((1/SSL_AR&D_Effic
acy[CRI_BINS])*10^9)
NG_Eff = .394
Nuclear_Eff = .34
Oil_Eff = .342
Operating__Costs[VH_CRI] = IF (Advanced_R&D=0) THEN
CL[VH_CRI]*(1/CL_Efficacy[VH_CRI])*Electricity_Costs*Electricity_Tax+SSL[VH_CRI]*(1
/SSL_MR&D_Efficacy[VH_CRI])*Electricity_Costs*Electricity_Tax ELSE
CL[VH_CRI]*(1/CL_Efficacy[VH_CRI])*Electricity_Costs*Electricity_Tax+SSL[VH_CRI]*(1
/SSL_AR&D_Efficacy[VH_CRI])*Electricity_Costs*Electricity_Tax
Operating__Costs[H_CRI] = IF (Advanced_R&D=0) THEN
CL[H_CRI]*(1/CL_Efficacy[H_CRI])*Electricity_Costs*Electricity_Tax+SSL[H_CRI]*(1/SSL
_MR&D_Efficacy[H_CRI])*Electricity_Costs*Electricity_Tax ELSE
CL[H_CRI]*(1/CL_Efficacy[H_CRI])*Electricity_Costs*Electricity_Tax+SSL[H_CRI]*(1/SSL
_AR&D_Efficacy[H_CRI])*Electricity_Costs*Electricity_Tax
Operating__Costs[M_CRI] = IF (Advanced_R&D=0) THEN
CL[M_CRI]*(1/CL_Efficacy[M_CRI])*Electricity_Costs*Electricity_Tax+SSL[M_CRI]*(1/SS
L_MR&D_Efficacy[M_CRI])*Electricity_Costs*Electricity_Tax ELSE
CL[M_CRI]*(1/CL_Efficacy[M_CRI])*Electricity_Costs*Electricity_Tax+SSL[M_CRI]*(1/SS
L_AR&D_Efficacy[M_CRI])*Electricity_Costs*Electricity_Tax
Operating__Costs[L_CRI] = IF (Advanced_R&D=0) THEN
CL[L_CRI]*(1/CL_Efficacy[L_CRI])*Electricity_Costs*Electricity_Tax+SSL[L_CRI]*(1/SSL_
MR&D_Efficacy[L_CRI])*Electricity_Costs*Electricity_Tax ELSE
CL[L_CRI]*(1/CL_Efficacy[L_CRI])*Electricity_Costs*Electricity_Tax+SSL[L_CRI]*(1/SSL_
AR&D_Efficacy[L_CRI])*Electricity_Costs*Electricity_Tax

Other_Eff = .35
Payback[VH_CRI] = -Diff_Upfront__Cost[VH_CRI]/Diff_Operating__Cost[VH_CRI]
Payback[H_CRI] = -Diff_Upfront__Cost[H_CRI]/Diff_Operating__Cost[H_CRI]
Payback[M_CRI] = -Diff_Upfront__Cost[M_CRI]/Diff_Operating__Cost[M_CRI]
Payback[L_CRI] = -Diff_Upfront__Cost[L_CRI]/Diff_Operating__Cost[L_CRI]
Percent_Coal = .538
Percent_NG = .149
Percent_Nuclear = .18
Percent_of__Lighting_SSL = Total_SSL/(Total_SSL+Total_CL)
Percent_Oil = .01
Percent_Other = .123
Primary__Quads = Delivered__Quads/(Combined_Ave___Efficiency*.92)
Purchase__Costs[VH_CRI] = IF (Advanced_R&D=0) THEN
CL_Purchase[VH_CRI]*CL_Upfront_Cost[VH_CRI]*(1/CL_Lifetime[VH_CRI])+SSL_Purcha
se[VH_CRI]*SSL_MR&D_Upfront_Cost[VH_CRI]*(1/SSL__MR&D_Lifetime[VH_CRI])
ELSE
CL_Purchase[VH_CRI]*CL_Upfront_Cost[VH_CRI]*(1/CL_Lifetime[VH_CRI])+SSL_Purcha
se[VH_CRI]*SSL_AR&D_Upfront_Cost[VH_CRI]*(1/SSL_AR&D_Lifetime[VH_CRI])
Purchase__Costs[H_CRI] = IF (Advanced_R&D=0) THEN
CL_Purchase[H_CRI]*CL_Upfront_Cost[H_CRI]*(1/CL_Lifetime[H_CRI])+SSL_Purchase[H_
CRI]*SSL_MR&D_Upfront_Cost[H_CRI]*(1/SSL__MR&D_Lifetime[H_CRI])
ELSE
CL_Purchase[H_CRI]*CL_Upfront_Cost[H_CRI]*(1/CL_Lifetime[H_CRI])+SSL_Purchase[H_
CRI]*SSL_AR&D_Upfront_Cost[H_CRI]*(1/SSL_AR&D_Lifetime[H_CRI])
Purchase__Costs[M_CRI] = IF (Advanced_R&D=0) THEN
CL_Purchase[M_CRI]*CL_Upfront_Cost[M_CRI]*(1/CL_Lifetime[M_CRI])+SSL_Purchase[
M_CRI]*SSL_MR&D_Upfront_Cost[M_CRI]*(1/SSL__MR&D_Lifetime[M_CRI])
ELSE
CL_Purchase[M_CRI]*CL_Upfront_Cost[M_CRI]*(1/CL_Lifetime[M_CRI])+SSL_Purchase[
M_CRI]*SSL_AR&D_Upfront_Cost[M_CRI]*(1/SSL_AR&D_Lifetime[M_CRI])
Purchase__Costs[L_CRI] = IF (Advanced_R&D=0) THEN
CL_Purchase[L_CRI]*CL_Upfront_Cost[L_CRI]*(1/CL_Lifetime[L_CRI])+SSL_Purchase[L_
CRI]*SSL_MR&D_Upfront_Cost[L_CRI]*(1/SSL__MR&D_Lifetime[L_CRI]) ELSE
CL_Purchase[L_CRI]*CL_Upfront_Cost[L_CRI]*(1/CL_Lifetime[L_CRI])+SSL_Purchase[L_
CRI]*SSL_AR&D_Upfront_Cost[L_CRI]*(1/SSL_AR&D_Lifetime[L_CRI])
Retrofit__Rate = .0042
SSL_Rebate__Program = 1
Tlmhr_Needed[VH_CRI] =
Tlmhr___Demand[VH_CRI]+CL_Retire[VH_CRI]+Retrofits[VH_CRI]*(1-
E&R_Ratio)+SSL_retire[VH_CRI]-CL[VH_CRI]-SSL[VH_CRI]
Tlmhr_Needed[H_CRI] =
Tlmhr___Demand[H_CRI]+CL_Retire[H_CRI]+Retrofits[H_CRI]*(1-
E&R_Ratio)+SSL_retire[H_CRI]-SSL[H_CRI]-CL[H_CRI]
Tlmhr_Needed[M_CRI] =
Tlmhr___Demand[M_CRI]+CL_Retire[M_CRI]+Retrofits[M_CRI]*(1-
E&R_Ratio)+SSL_retire[M_CRI]-CL[M_CRI]-SSL[M_CRI]

Tlmhr_Needed[L_CRI] = Tlmhr___Demand[L_CRI]+CL_Retire[L_CRI]+Retrofits[L_CRI]*(1-E&R_Ratio)+SSL_retire[L_CRI]-SSL[L_CRI]-CL[L_CRI]
Tlmhr___Demand[VH_CRI] = Klmhr_per_sqft_*Bld_sqft[VH_CRI]/10^9
Tlmhr___Demand[H_CRI] = Klmhr_per_sqft_*Bld_sqft[H_CRI]/10^9
Tlmhr___Demand[M_CRI] = Klmhr_per_sqft_*Bld_sqft[M_CRI]/10^9
Tlmhr___Demand[L_CRI] = Klmhr_per_sqft_*Bld_sqft[L_CRI]/10^9
Total_CL = CL[VH_CRI] + CL[H_CRI] + CL[M_CRI] + CL[L_CRI]
Total_Cost =
Purchase__Costs[VH_CRI]+Purchase__Costs[H_CRI]+Purchase__Costs[M_CRI]+Purchase__Costs[L_CRI]+Operating__Costs[VH_CRI]+Operating__Costs[H_CRI]+Operating__Costs[M_CRI]+Operating__Costs[L_CRI]
Total_SSL = SSL[VH_CRI] + SSL[H_CRI] + SSL[M_CRI] + SSL[L_CRI]
TWh[VH_CRI] = kWhr[VH_CRI]/(10^9)
TWh[H_CRI] = kWhr[H_CRI]/(10^9)
TWh[M_CRI] = kWhr[M_CRI]/(10^9)
TWh[L_CRI] = kWhr[L_CRI]/(10^9)
Years__Payback[VH_CRI] = IF (Payback[VH_CRI] < 10) AND (Payback[VH_CRI] > 0) THEN Payback[VH_CRI] ELSE 15
Years__Payback[H_CRI] = IF (Payback[H_CRI] < 10) AND (Payback[H_CRI] > 0) THEN Payback[H_CRI] ELSE 15
Years__Payback[M_CRI] = IF (Payback[M_CRI] < 10) AND (Payback[M_CRI] > 0) THEN Payback[M_CRI] ELSE 15
Years__Payback[L_CRI] = IF (Payback[L_CRI] < 10) AND (Payback[L_CRI] > 0) THEN Payback[L_CRI] ELSE 15
Bld_sqft[CRI_BINS] = TIME
CL_Efficacy[CRI_BINS] = TIME
CL_Lifetime[CRI_BINS] = TIME
CL_Upfront_Cost[CRI_BINS] = TIME
Electricity_Costs = GRAPH(TIME)
(0.00, 0.069), (62.8, 0.067), (126, 0.069), (188, 0.072), (251, 0.073)
Epidemic__Rate =
GRAPH((SSL[VH_CRI]+SSL[H_CRI]+SSL[M_CRI]+SSL[L_CRI])/(CL[VH_CRI]+CL[H_CRI]+CL[M_CRI]+CL[L_CRI]+SSL[VH_CRI]+SSL[H_CRI]+SSL[M_CRI]+SSL[L_CRI]))
(0.00, 0.00), (0.1, 0.00), (0.2, 0.0008), (0.3, 0.0012), (0.4, 0.002), (0.5, 0.0024), (0.6, 0.003), (0.7, 0.0035), (0.8, 0.004), (0.9, 0.0044), (1, 0.0044)
Percent__SSL[CRI_BINS] = Years__Payback[CRI_BINS]
Percent__SSL_IF[CRI_BINS] = Years__Payback[CRI_BINS]
SSL_AR&D_Efficacy[CRI_BINS] = TIME
SSL_AR&D_Lifetime[CRI_BINS] = TIME
SSL_AR&D_Upfront_Cost[CRI_BINS] = TIME
SSL_MR&D_Efficacy[CRI_BINS] = TIME
SSL_MR&D_Upfront_Cost[CRI_BINS] = TIME
SSL__MR&D_Lifetime[CRI_BINS] = TIME

APPENDIX E. Summary of Current Public Policies Related to SSL

Policy	Part of Government	Description of the Policy
R&D Funding for SSL	Department of Energy (DOE)- Office of Energy-Efficiency and Renewable Energy-Building Technologies Program	The DOE has supported R&D on both LED and OLED technology under its Building Technologies Program. R&D funding has been made available for a spectrum of activities from basic research to product development. These government funding opportunities are often supplemented with a cost-share ranging from 20-50%. More information is available from: http://www.netl.doe.gov/ssl/
Sponsors Meeting & Workshops on SSL	Department of Energy-Office of Energy-Efficiency and Renewable Energy-Building Technologies Program	Meetings and workshops were partially sponsored by the DOE; bringing together SSL experts from industry, academia and government. From these meeting, industry roadmaps were created in which technical targets were established and core challenges discussed. These reports are available from: http://www.netl.doe.gov/ssl/publications.html
Provide Information Portal on SSL	Sandia National Laboratory	Maintains a current website on SSL. This website contains an overview of the technology; current and archived technical and business news on SSL; an overview of SSL programs in foreign countries; worldwide links to organizations involved in SSL; and information about U.S. government programs for SSL. This website can be accessed at: http://lighting.sandia.gov/
Established SSL Industry Alliance	Department of Energy-Office of Energy-Efficiency and Renewable Energy-Building Technologies Program	In July 2004 the DOE selected the Next Generation Lighting Industry Alliance (NGLIA) to serve as its partner in research, development and demonstration activities for SSL. The industry alliance is expected to provide and manufacturing and commercialization focus for DOE SSL efforts. No government funding is used for this Alliance.
National Initiative for SSL (Proposed Legislation)	U.S. Congress	In 2001, Senators Bingaman (NM) and Mike DeWine (OH) introduced S.1166 which called for the establishment of a "Next Generation Lighting Initiative" in the DOE. The bill would authorize $50 million per year for 10 years to develop SSL. This bill was included in the S.1766 "Energy Policy Act of 2002," and subsequently also included in S.2095 "The Energy Policy Act of 2003" introduced in February 2004. As of December 2004 this legislation has not been approved.
R&D on Related Technologies	Defense Advanced Research Project Agency (DARPA); Office of Naval Research (ONR); Sandia National Laboratory; Berkeley National Laboratory	DARPA has a program to develop semiconductor U.V. lighting sources to detection biological agents- This UV technology could be useful for SSL. ONR has been a long supporter of research on wide-bandgap semiconductors. Sandia and Berkeley (both U.S. national laboratories) both have research programs on SSL.

APPENDIX F. Table of SSL CMP Model Elements